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A POTENTIOMETRIC PETROLEUM RESERVOIR ANALYZER

"The Design and Construction of an Electric Analog Simulator Applicable to the Analysis of Natural Petroleum Reservoirs"

Gerald A. Martin

May 1, 1952

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A POTENTIOMETRIC PETROLEUM RESERVOIR ANALYZER

"The Design and Construction of An Electric Analog Simulator Applicable to the Analysis of Natural Petroleum Reservoirs"

A DISSERTATION

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DEPARTMENT OF CHEMICAL AND PETROLEUM ENGINEERING

by

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EDMONTON, ALBERTA

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THE PROBLEM

The problem, with which this investigation was concerned, was the design and construction of an electrical flow model, which could be applied by analogy to flow problems encountered in the analysis of petroleum reservoirs, especially those dealing with the design of secondary recovery projects.

ABSTRACT

A Potentiometric Petroleum Reservoir Analyzer

"The Design and Construction of an Electric Analog Simulator Applicable to the Analysis of Natural Petroleum Reservoirs."

Many reservoir engineering problems are essentially problems in fluid mechanics. The differential equations describing the reservoir flow system are not easily solved, due very often, to an inability to express mathematically the complex boundary conditions which prevail. However, in most cases, solutions may be obtained by the use of analogy.

The fundamental requirements for the existence of an analogy between two physical systems are outlined with special reference to fluid flow and electron flow phenomena. To meet these fundamental requirements it is necessary to introduce certain assumptions and restrictions concerning the nature of the fluid flow.

The potentiometric model selected for this study is capable of solving problems involving the two dimensional steady state flow of single phase fluids through porous media. More complex models capable of solving unsteady state flow problems are possible, but were considered beyond the scope of the present research program.

The model developed during this investigation is semi-automatic in operation, and employs electronic controlled null-balance motors. The machine is capable of locating the isopotential lines of a flow pattern, and is also capable of plotting the flow lines directly by

the use of a four probe search array. The self balancing potentiometer is designed so that the process of evaluating the transit time of a particle along a flow line is reduced to a simple summation of successive potentiometer readings. The arrangements for duplicating the flow pattern, existing in the reservoir, are outlined; and the associated measuring and automatic control circuits are described in detail.

The model's performance and precision are evaluated by analyzing an idealized "five-spot" flood pattern. The results so obtained are compared with published results of previous investigations of the same problem. This comparison indicates the model is performing satisfactorily with an average error of one percent. Experience gained in this preliminary operation indicates certain improvements in the model are desirable. These proposed improvements are outlined.

A detailed operations manual for the machine describing the setting-up procedure, operation, and maintenance of the model is included as an appendix to the main report.

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A POTENTIOMETRIC PETROLEUM RESERVOIR ANALYZER

"The Design and Construction of an Electric Analog Simulator Applicable to the Analysis of Natural Petroleum Reservoirs"

Introduction

Oil and gas reservoirs found in nature, present problems in fluid mechanics which are difficult to solve by analytical methods. The complex and irregular structures, encountered in most reservoirs, produce boundary conditions which would result in cumbersome equations if expressed mathematically. No two reservoirs present the same set of boundary conditions. Past experience therefore, can only serve as a guide, when determining the most efficient method of producing a specified field. Direct experimentation on the oil reservoir is possible to only a limited extent, since early errors cannot be rectified, nor their effects eliminated.

If a small scale model could be constructed duplicating all conditions encountered in the reservoir, it would be possible to conduct repeated trials using the model, and so arrive at the most efficient production procedure.

A scale model of the field could be constructed using a porous medium filled with the appropriate fluids under a suitable pressure. Trial runs, employing various producing methods, could then be made and the most satisfactory production method selected. The method chosen by means of the model study might then be applied to the field with some confidence. Such models[13] have been constructed to duplicate conditions in isolated section of reservoirs. However, to duplicate an entire field by this method, would be a large under-

taking, since it is possible to obtain only limited scale reduction by the use of this type of model. The limited scale reduction is due to the fact that the physical characteristics of the fluids employed must be reduced in scale, and yet retain the same relative effect on flow characteristics.

A different approach to the problem has so far, produced better results. Darcy's law, governing the flow of fluids through porous media, is basically a rate equation of the form:

$$\text{Rate of flow} = \frac{\text{Driving Force}}{\text{Resistance}}$$

The similarity between Darcy's law, and Ohm's law governing electrical flow, has been recognized. Attempts have been made to construct an electrical analogy to the oil reservoir, and to apply the results obtained from electrical measurements to the solution of the fluid flow equations.

THEORETICAL DEVELOPMENT OF THE ANALOGY

The existance of an analogy between fluid flow through a porous medium, and electron flow through a conducting medium, depends upon the fundamental similarity between the equations governing such flow. These equations are, Laplace's equation of continuity and the rate equations represented by Darcy's Law and Ohm's Law. The following discussion will compare these equations and deal with the conditions, which must be satisfied, before the analogy between the two phenomena is complete.

The Equation of Continuity in Fluid Flow

The development of Laplace's equation of continuity for the case of a compressible fluid flowing through a porous medium, results in the expression,

$$\left[\frac{\Delta}{\Delta x}(\rho v_x)+\frac{\Delta}{\Delta y}(\rho v_y)+\frac{\Delta}{\Delta z}(\rho v_z)\right]\Delta x.\Delta y.\Delta z = -V_o f \frac{\Delta \rho}{\Delta t} \qquad (1)$$

(See appendix A, Page (i) for the development of this expression.)

The Rate Equation in Fluid Flow (Darcy's Law)

Darcy's law describing the rate of flow of a fluid through a porous medium may be expressed mathematically as follows:

$$v_x = -\frac{k_x}{\mu}\frac{\Delta P}{\Delta x} \qquad (2)$$

Equation (2) assumes the absence of gravitational attraction acting on the fluid.

Darcy's law may now be combined with the equation of continuity to give equation (3).

$$\left[\frac{\Delta}{\Delta x}\left(\rho\frac{k_x}{\mu}\frac{\Delta P}{\Delta x}\right)+\frac{\Delta}{\Delta y}\left(\rho\frac{k_y}{\mu}\frac{\Delta P}{\Delta y}\right)+\frac{\Delta}{\Delta z}\left(\rho\frac{k_z}{\mu}\frac{\Delta P}{\Delta z}\right)\right]\Delta x.\Delta y.\Delta z = V_o f \frac{\Delta \rho}{\Delta t} \qquad (3)$$

Note: See page 69 for an explanation of the nomenclature used.

For the purpose of the subsequent discussion, equation (3) will be referred to as the general equation describing fluid flow through porous media.

The Equation of Continuity in Electron Flow.

Laplace's equation of continuity may be developed for the case of electrical energy flowing through a conducting medium. If the conducting medium be considered to possess the property of capacitance the following expression results:

$$\left[\frac{\Delta}{\Delta x'}\left(\frac{i_{x'}}{A_{x'}}\right)+\frac{\Delta}{\Delta y'}\left(\frac{i_{y'}}{A_{y'}}\right)+\frac{\Delta}{\Delta z'}\left(\frac{i_{z'}}{A_{z'}}\right)\right]\Delta x'.\Delta y'.\Delta z' = \frac{\Delta(C_E E)}{\Delta t'} \qquad (4)$$

(The development of equation (4) is presented in appendix A, page (iii)

The Rate Equation in Electron Flow

Ohm's law for electrical energy flow through a conducting medium may be expressed as follows:

$$i_x = \frac{\Delta E_{x'}}{R_{x'}}$$

Since the electrical resistance Rx' is directly proportional to the distance traversed, $\Delta x'$, and inversely proportional to the specific conductivity, σ, and cross sectional area, $A_{x'}$, Ohm's law may be rewritten as:

$$i_{x'} = \sigma A_{x'} \frac{\Delta E}{\Delta x'}$$

This expression may now be combined with the equation of continuity to give:

$$\left[\frac{\Delta}{\Delta x'}\left(\sigma\frac{\Delta E}{\Delta x'}\right)+\frac{\Delta}{\Delta y'}\left(\sigma\frac{\Delta E}{\Delta y'}\right)+\frac{\Delta}{\Delta z'}\left(\sigma\frac{\Delta E}{\Delta z'}\right)\right]\Delta x'.\Delta y'.\Delta z' = \frac{\Delta(C_E E)}{\Delta t'} \qquad (5)$$

Equation (5) is the general equation describing the flow of electrical current through a conducting medium.

The Analogy

The study of a physical system involves the consideration of three items, the system variables, the system constants and parameters, and finally the equations describing the system. In the case of an oil reservoir the system variables are the formation pressure (temperature is also a variable but one ordinarily not considered) and the flow rate, which in general will vary with position and time. The system parameters may be classified in two groups; those, such as permeability, porosity and geometrical shapes, which are characteristic of the medium, and viscosity, compressibility and density, which are characteristic of the fluid. The equation describing the flow of fluid in a reservoir has been presented as equation (3) in the above section.

With this information available, it is possible to visualize a variety of physical systems analogous to an oil reservoir. An analogous system will possess a set of variables, corresponding to those of the prototype, a corresponding set of parameters, and a set of equations of identical form to those encountered in the prototype.

A prototype system and an analogical system may be related by equating each variable and parameter of one system to a proportionality constant times the corresponding variable or parameter of the other system. The end result is then a set of transformation equations, by which the parameters and variables of one system can be computed provided those of the other system are known.

These analogous systems may be employed to advantage in two situations often encountered in practice. For example, suppose all the parameters of a given system are known, and the equations are available; it is then possible to evaluate the variables by analytical methods. This may introduce mathematical complexities that cannot be handled. By the use of the transformation equations, it is possible to construct an analogous system. This system may be set in operation, its variables measured and, by again using the appropriate transformation equations, the corresponding prototype variables may be evaluated to obtain the desired result. A model analogy, constructed and used on this basis, is termed a computer. Suppose now, that the values of some of the parameters in the prototype are unknown, due to the fact that they are inaccessible, or that the phenomena produced by the system proceed with such slowness that it is impossible to carry out the necessary observations to determine them. Suppose also that the equations governing the system are known. It is now possible to construct an analogical model embodying precise values of the known parameters, and a series of adjustable values for the unknown parameters. Such a model is called a simulator. It is now possible by repeated trials to adjust the values of unknown parameters until the variables of the simulator match the observed values of accessible variables of the prototype. The actual, or at least mathematically equivalent, structure of the prototype has now been determined, and the simulator becomes a computer, capable of predicting the future behavior of the prototype.

The Formation of the Analogy

When an attempt is made to form an analogy between fluid flow through a porous medium, and electron flow through a conducting medium, the first requirement to be satisfied is the identity of form of the respective equations.

It is convenient at this point to examine more closely the equations involved:

$$\left[\frac{\Delta}{\Delta x}\left(\rho\frac{k_x}{\mu}\frac{\Delta p}{\Delta x}\right)+\frac{\Delta}{\Delta y}\left(\rho\frac{k_y}{\mu}\frac{\Delta p}{\Delta y}\right)+\frac{\Delta}{\Delta z}\left(\rho\frac{k_z}{\mu}\frac{\Delta p}{\Delta z}\right)\right]\Delta x\Delta y\Delta z = V_0 f\frac{\Delta\rho}{\Delta t} \quad (3)$$

the equation for fluid flow and,

$$\left[\frac{\Delta}{\Delta x'}\left(\sigma\frac{\Delta E}{\Delta x'}\right)+\frac{\Delta}{\Delta y'}\left(\sigma\frac{\Delta E}{\Delta y'}\right)+\frac{\Delta}{\Delta z'}\left(\sigma\frac{\Delta E}{\Delta z'}\right)\right]\Delta x'\Delta y'\Delta z' = \frac{\Delta\left(C_E E\right)}{\Delta t'} \quad (5)$$

the equation for electrical energy flow.

While these equations are in many respects similar in their present form, certain differences are evident. For example, the pressure, p, in the fluid system is analogous to the potential, E, in the electrical system; yet E appears on the right hand side of equation (5) while p does not appear in the corresponding place in equation (3). Also the specific conductivity, σ, which is a parameter of equation (5) is a constant and at the same time analogous to the expression, $\rho\frac{k}{\mu}$, an obvious variable.

Certain assumptions must be introduced at this point to overcome these discrepancies. Various assumptions are possible, and lead to different analogies. The analogies may be arbitrarily grouped into two general classes (with three sub-classifications in

each general class) according to the assumptions made in reducing equations (3) and (5) to similar form. The general division is introduced due to the existence of two possible methods of producing a variation in the effective specific conductivity, σ, of the medium. One possible solution is to vary the thickness of the conducting sheet proportionally with permeability, k, or the permeability-viscosity ratio, $\frac{k}{\mu}$. This of course destroys the geometrical similarity between model and prototype in the z direction. Therefore whenever such assumptions are made the analogy becomes restricted to two dimensional flow.[24] The second possible solution is to destroy the continuity of the model's conducting medium, replacing it with a resistance network connecting arbitrarily selected points.[4] The resistance between points may now be selected at will. This rather drastic treatment also destroys the continuity of all variables with respect to position, continuity with time, alone remaining.

The sub-classifications occur due to the existance of various methods of reducing the right hand side of equation (5) to similarity with the corresponding expression in equation (3).

The simplest assumption that can be made is to restrict the problem to steady state flow conditions. This immediately reduces the right hand side of the equation to zero. When this restriction is combined with the concept of a continuous conducting sheet contoured, to represent variations in the permeability-depth product of the reservoir, as previously outlined, it is possible to form an exact analogy between the two systems.

Since in general, the density, ρ, and the viscosity, μ, are functions of the pressure, it is possible to define a new quantity,[24] ϕ, such that

$$\phi = \int \frac{\rho}{\mu} dP .$$

If now, this function is introduced into the differential form of equation (3) and also if in equation (3), x is put equal to, $a x'$, y is put equal to, $a y'$, and z is put equal to, $b z'$, where, b, is not necessarily constant, and if in addition all flow in the z direction is ignored, equations (3) and (5) may be rewritten as

$$\left[\frac{\partial}{\partial x'} \left(k_x b \frac{\partial \phi}{\partial x'} \right) + \frac{\partial}{\partial y'} \left(k_y b \frac{\partial \phi}{\partial y'} \right) \right] = 0 \qquad (6)$$

and

$$\left[\frac{\partial}{\partial x'} \left(\sigma \frac{\partial E}{\partial x'} \right) + \frac{\partial}{\partial y'} \left(\sigma \frac{\partial E}{\partial y'} \right) \right] = 0 \qquad (7)$$

It is apparent that the two equations are now similar in form. It is possible to equate the two parameters, σ, and, $k_x b$, and, $k_y b$, provided the permeability in the x direction equals the permeability in the y direction at any point.

The transition equation relating the fluid resistance to the electrical resistance then becomes,

$$\sigma = A k b$$

where A is an arbitrary proportionality constant or scale factor. The factor, b, was previously defined as the ratio of prototype thickness to model thickness. If this ratio is substituted for it can be seen that the required model thickness, z', is given by the expression

$$z' = \frac{A k z}{\sigma} .$$

This is the desired transition equation, and the analogy is now complete, since the function, ϕ, may be equated to, FE, where F is another arbitrary scale factor, without further alteration to the equations.

We have now developed two transition equations which may be summarized as follows,

$$\frac{\text{Fluid flow resistance}}{\text{Electron flow resistance}} = \frac{R_F}{R_E} = A$$

$$\frac{\text{Fluid driving force}}{\text{Electron driving force}} = \frac{P}{E} = F$$

Two other transition equations or ratios exist, which may be derived from those already presented. These are, first, the ratio between Volumetric rate of flow, Q, in barrels per day, and the quantity of electrons flowing, i, in coulombs per second or amperes; and second, the ratio between the prototype time, t, in days and the model time, t', in seconds.

Consider the rate equations

$$Q = \frac{P}{R_F}$$

and $$i = \frac{E}{R_E}$$

The ratio $\left(\frac{Q}{i}\right)$ becomes,

$$\frac{Q}{i} = \frac{P}{E} \cdot \frac{R_E}{R_F} = \frac{F}{A}.$$

In the type of model we are considering, it is usually more convenient to select this ratio arbitrarily and allow the ratio, $\frac{P}{E}$, to be defined from this.

The discharge time of a system, is normally obtained from the product of the resistance and capacitance of the system, and the ratio between two systems would be given by,

$$\frac{t}{t'} = \frac{C_F}{C_E} \cdot \frac{R_F}{R_E}$$

However, in the case of steady state flow, to which the present discussion is limited, there is no capacity effect considered, hence the ratio $\frac{C_F}{C_E}$ is indeterminate and another development is required to determine the model time t.

The local rate of advance of a fluid particle along any stream line in the reservoir, may be considered one dimensional flow and may be evaluated by applying Darcy's Law:

$$v = -\frac{k}{\mu}\frac{dP}{dS}$$

where v is the macroscopic or bulk velocity. The actual particle velocity, $\frac{\Delta S}{\Delta t}$, may be found by dividing the macroscopic velocity by the porosity, f, to give the relation,(24)

$$\frac{\Delta S}{\Delta t} = -\frac{k}{\mu f} \cdot \frac{\Delta P}{\Delta S}$$

Substitute in the equation, the function, $\Delta \phi$,

and the velocity now becomes

$$\frac{\Delta S}{\Delta t} = -\frac{k}{\mu f} \cdot \frac{\mu}{\rho} \frac{\Delta \phi}{\Delta S}.$$

Let the reservoir distance, ΔS, equal 'a', times the model distance $\Delta S'$, and the potential function, ϕ, of the reservoir equal F

times the potential, E. The reservoir time, Δt, may now be evaluated from the expression

$$\Delta t = - \frac{a^2}{F} \cdot \frac{\rho f}{k} \cdot \frac{(\Delta s')^2}{\Delta E}$$

(Reference 24 and 12)

This is not a true transformation equation since the model time does not appear. However, the model transit time is not a variable that can be conveniently measured, and, therefore, the above equation is used whenever an estimate of the transit time is required.

The more complex problem of the analogy between unsteady state flow in a reservoir, and unsteady state flow in an electrical system is analyzed in detail in Appendix B. The general method involves the introduction of the analogy existing between the ability of a condenser to accumulate electrical energy, and the ability of a compressible fluid to accumulate both energy and fluid in a fixed volume.

An equation of state must also be introduced to relate pressure and fluid density.

This analogy[4] leads to a very versatile model, generally referred to as an "Electric Analyzer", which is capable of reproducing the pressure decline curves for individual wells of a reservoir operating under expansion drive or gas cap drive.

This model may be constructed using a continuous conducting sheet, or a resistance network to simulate the porous medium. The electrical capacity is added to simulate the storage capacity of small blocks of the reservoir. Provision is also made to simulate the effects of a partial water drive, gas cap drive[24] and artificial flooding.

A Description of Models in Use

(a) Historical Development of Electrical Analogs

The earliest recorded use of the analogy existing between fluid flow and electron flow, was a study, conducted by G.I. Taylor and C.F. Sharman.[29] These men investigated the analogy existing between the irrotational flow of a compressible fluid in two dimensions and the flow of electricity in a conducting sheet of variable thickness. This analogy was used to investigate the flow patterns existing about airfoil cross-sections. It is interesting to note that the present potentiometric model with minor modifications could be adapted to this study. The method employed, involved the contouring, by successive approximations, of the conducting sheet to correspond to the variations in fluid density.

The first application of the analogy to oil reservoir problems was made by B. D. Wyckoff, H. G. Botset and M. Muskat in 1933.[31] The model devised by these investigators was of the migrating ion type in which a potential field was applied to a conducting sheet containing an ion indicator. This basis model has been improved by later work, and remains a useful model to the present time.

Hurst and McCarty[10] in 1941 made the first published attempt to apply the preciseness of potentiometry to the study of oil reservoir migration problems. Their method involved a single probe mapping of the potential field to obtain a system of equipotentials. The current lines were then constructed graphically by drawing a system of curves interesecting the equipotential lines at right angles. From this resulting map a chart was drawn for each flow line showing potential as a function of distance along the line.

Each chart was then differentiated graphically to obtain a curve of voltage gradient as a function of distance. The area under each curve was then integrated with a planimeter and a new chart drawn for each current line showing this integral as a function of distance. The ordinates of this last curve were proportional to the transit time between any two points. This was the desired result. This laborious procedure prevented wide application of the method, and as far as is known this was the only attempt made to apply it. In 1947, D. B. Lee[12] introduced several simplifications to the procedure which permitted studies to be conducted using the potentiometric principle. The first simplification was the use of a pantograph to transfer the isopotential lines directly from the pool to the map, thus avoiding the necessity of replotting. The graphical integrations were avoided by making use of the relation:

$$\Delta t \propto \frac{\Delta S^2}{\Delta E}$$

If ΔS is sufficiently small and ΔE were maintained constant then

$$\Delta t \propto \Delta S^2$$

and Δt could be scaled off the map directly by means of a square scale ruler. The greatest advance was the introduction of the four probe array, which is described more fully in a later section; together with the orientation of the probes and the balancing of the potentiometer by phase sensitive motors. A totalizing device to sum the reciprocals of the voltage was also suggested by Lee. It is not clear from the published literature how many of these devices Lee actually experimented with and how many were merely suggestions. Certain difficulties in the design of the totalizer, would indicate that the author was making a general suggestion rather than describing a piece of equipment.

Redmond[25], Wolf[30], Muskat[24], and Marshall and Oliver[15] all describe studies using a model similar in nature to the single probe method described by Lee.

The next advance in technique was described by W. A. Bruce[4] in 1943. This advance was the inclusion of the additional analogy between fluid volumetric expansion and electrical capacitance as sources of driving energy, and resulted in the development of a new model known as the electrical analyzer. The chief use of this model is the investigation of "time changes" within the reservoir.

This model has been improved by employing a resistance network[5] rather than a contoured electrolytic sheet, to simulate the porous medium. Thus giving a model whose resistance parameters may be varied at will. A further improvement of the model has been the inclusion of a unit to simulate the effect of a gas cap drive.

The Migrating Ion Model

This model[33] was the first electrical analogy to be applied to reservoir problems. The porous medium of the reservoir is represented by a gelatine mat, moulded to the required shape, and rendered conducting by the inclusion of zinc ammonium chloride salt solution. The injection wells are represented by hollow plastic tubes with capillary tips piercing the gelatine mat. These plastic tubes are filled with gelatine, containing copper ammonium chloride and ammonium hydroxide solution. Electrical contact is provided by the insertion of a platinum electrode into the plastic tube. The producing wells are represented by tubes similar to those used as input points, except for the use of zinc ammonium chloride to render the gelatine conducting.

In operation, the input and output wells are arranged to suit the conditions it is desired to duplicate. A direct current is passed between the input and output wells. The current through each individual well is

adjusted by means of a variable resistor, until it is proportional to the production or injection rate of the well concerned.

When the current has been switched on, the colored copper ammonium ions migrate from the imput electrodes and their progress may be followed visually or recorded by means of a camera. The portion of the field invaded by the colored ions indicates the portion of the reservoir that would be invaded by fluid originating at the input wells. This invasion pattern represents the solution to the problem that the model was designed to solve.

The potential gradient existing in the sensitized mat of the model must be maintained at a sufficiently high value to result in ion migration velocities greatly in excess of the ion velocities produced by diffusion. Therefore, the physical size of the conducting sheet must be made small in order to maintain a fairly high potential gradient, without using excessive voltages. This generally limits the model to the study of small portions of the reservoir. The dependence on ion migration velocities, to depict the model behavior, gives results that are considered to be of a qualitative nature only, especially in regions of low potential gradient.

The Potentionmetric Model

The potentiometric model has appeared in several forms. The basic units are similar in all forms of the model, the differences result from the incorporation of various auxilliary units, to reduce the labor involved in evaluating the model's performance.

The main portion of the model is the pool unit, containing a slightly conducting liquid, held in a basin contoured to represent the reservoir under consideration. Electrodes, representing input and output wells, are inserted through the bottom into the electrolyte.

The remainder of the pool unit consists of electrical circuits designed to control the currents to and from each electrode. This essential auxilliary equipment, consists of a potentiometer circuit, a voltage control circuit, and a null indicator, which is really an essential part of the potentiometer.

The operating procedure for this form of the potentiometric model is rather laborous. After the pool model has been constructed and put in operation, the electrode currents are adjusted to the required values. An isopotential map is drawn from the model, maintaining a constant potential difference between successive isopotential lines. On this map a series of flow lines are drawn, crossing the isopotential lines at right angles. The distance between successive isopotential lines is measured along each flow line. The transit time between each isopotential is then computed using the relation,

$$\Delta t = \frac{a^2}{F} \cdot \frac{\rho f}{k} \cdot \frac{(\Delta s')^2}{\Delta E}$$

These time increments are then added together along each stream line to give the total transit time. Maps may now be prepared showing the invasion pattern after any desired time interval. This is the final result obtained from the model study.

An improvement in the potentiometric model is the incorporation of a four probe search array.[12] This refinement allows the direct plotting of the stream lines without the necessity of constructing them from an isopotential map. The four probe array consists of four electrodes positioned in the form of a cross. This array is pivoted about one of the electrodes. One pair of electrodes, which will be referred to as the equipotential probes, are connected to the null indicator. The array is rotated until a minimum signal

is received. These two electrodes are then on an equipotential line. The second pair of probes will then be oriented so that the line joining them coincides with a flow line. The positions of the probes are now recorded on the map. The potentiometer is connected to these probes and measures the potential drop, $\triangle E$, between them. As before, the transit time between two points is given by the relation:

$$\Delta t = -\frac{a^2}{F}\cdot\frac{\rho f}{k}\cdot\frac{(\Delta s')^2}{\Delta E}$$

Since $\triangle s'$ is now the spacing between the two probes, it is a constant, and the transit time is proportional to the reciprocal of the voltage. A flow line may be mapped by placing one of the current probes at a desired starting point, orienting the array, marking the location of the second probe, moving the array until the first probe occupies this position, and then reorienting the array. By proceeding in this manner, the entire flow line map may be constructed.

Two other improvements may be added to speed up the operation of the potentiometric model. These consist of a phase sensitive reversible induction motor, controlled by the null indicator, which automatically orients the four probe array. A similar motor is used to drive the potentiometer shaft, and keep the potentiometer balanced. A totalizing device may also be connected to the potentiometer to record and total the reciprocals of the voltage readings.

The Electrical Analyzer

This model analogy was first devloped by W. A. Bruce of the Carter Oil Company,[4] To date, this is the only model developed to handle compressible flow, in the cases of a single or two phase reservoir.

The central section of this model consists of a pool unit, representing the oil reservoir. This unit may be a contoured model containing a liquid electrolyte. In which case, additional electrodes located at the centres of arbitrarily assigned blocks must be included. Condensers, of a value determined by the relation

$$C_E = B V_o f_c$$

for each block, are connected to these electrodes. Or, the pool may be represented by a resistance network connecting the centres of the chosen blocks. Condensers are again connected to these centre points. A power supply is required, which will deliver a D.C. voltage of variable value, which, when once set, will retain a constant value regardless of random mains fluctuations.

The Injector Unit must supply current to simulate the action of an input well. In general an input well provides a given input rate, independent of the bottom hole pressure. Due to this fact, a constant current charging device must be used in the input unit of the analyzer. This requires that the current be supplied through a pentode tube to each input well, or to each group of input wells that may be considered to be operating against the same bottom hole pressure.

The Discharge or Production unit is similar to the input unit except that it allows a constant discharge rate, equivalent to the producing rate of the well it represents. Here again one pentode may control a group of wells provided the bottom hole pressures are the same.

The design of the Water Drive unit depends upon the fact that regardless of the shape of the producing area of a reservoir and the location

of the wells in it, the isopotentials in the surrounding aquifer ultimately become circles at some point away from the field. A small scale potentiometric model of the field, including a portion of the surrounding aquifer is used to determine the shape of the adjacent isopotentials and the point at which they may be considered as circles. The resistance between adjacent noncircular isopotentials can be determined directly from the model, while the resistance between more remote circular isopotentials, is determined from the relation,

$$R_f = \frac{\nu}{2\pi kz} \cdot \ln \frac{r_n}{r_{(n-1)}}$$

$$V_o = z\pi \left(r_n^2 - r_{(n-1)}^2 \right)$$

(These equations developed by W. A. Bruce. Reference 4 in Bibliography.)

With values of R and V_o obtained in this manner a resistance - condenser chain may be constructed to represent the surrounding aquifer and is called the water drive unit.

A Gas Drive Unit has been described in detail by Schaeffer and a circuit diagram is available. This unit required two pentodes for each point in the reservoir to be supplied with a gas cap drive. These will normally be only a few blocks near the centre of the field in contact with a gas cap.

The timer consists of a master oscillator, producing a D.C. pulse at some fixed time interval. This can be accomplished by means of a thyratron discharge circuit or by a rotating contact device. Selector or counting circuits are required to obtain multiples of this fundamental time unit. The timer unit acts as the master automatic control, switching in all of the auxilliary circuits as required, to duplicate the production history of the oil reservoir.

Details on the design of this analogical model are not given in the literature, and a complete description is beyond the scope of this work.

A brief summary of the electrical equipment required for the construction of each of the models is given in Table I.

Characteristics and Limitations of the Models

A comparison of these models from the standpoint of their characteristics and limitations is largely a review of the mathematical assumptions employed in attaining the analogy. The characteristics of a particular model are determined by the method employed of reproducing the variation of any parameter of the prototype reservoir. Similarily the limitations of any model are a direct result of the mathematical assumptions made in its construction.

In general, the analogical model must deal with variations in the properties of both fluid and porous medium as these alter with changes in position and time. None of the models, developed at present, are capable of reproducing all of these variations. Table II presents a list of these variations and the methods of dealing with the variation, employed by each model.

TABLE I

Comparison of Models from Standpoint of Equipment Required

Equipment	Migrating Ion	Potentiometric	Electrical Analyzer
Power Supply To Model	D. C. Power Supply should be variable up to 300 volts, stabilization is desirable	A. C. Power supply to pool unit, D.C. supply to amplifiers, requires Auto-Transformer or variac.	D. C. Power Supply should be variable up to 300 volts, stabilization would be an advantage.
Input & Output Regulators	Variable Resisters D. C. Milliameters	Variable Resistors A. C. Milliameters or measure voltage drop across a calibrated resistor by using potentiometer	Constant current Pentode circuit adjustments made by altering bias. D. C. milliameters used for measuring.
Pool Unit	Jelly + electrolyte molded to required shape. Colored ions supplied at Input wells Model must be physically of small dimensions. Wells are hollow tubes filled with jelly, fitted with platinum electrodes.	Liquid electrolyte. Held in container shaped to represent reservoir. Electrodes inserted to represent input and output wells.	May be same as that used for potentiometric model with condensers attached to electrodes representing wells. Extra electrodes must be added to supply capacity to portions not being drained by wells. Or a resistance network may be constructed to represent the pool.
Water Drive Unit	None	None	A resistance-condenser network, to represent aquifer.
Gas Drive Unit	None	None	Precharged condensers added to network, precharging done ith Pentodes.

Measuring and Recording Instruments	Visual Inspection. Camera Recording Planimeter measurement of area to obtain percent of total area flooded.	Potentiometer used to trace iso-potential lines, recorded by pantograph or plotting. Flow lines drawn graphically or directly plotted by 4-probe array. Transit times evaluated along flow lines. Invasion patterns plotted. Planimeter used measure area flooded.	Timing Mechanism on simple model may be manual, requires timer to handle complex model. Potentials determined by means of electron voltmeter read at timed interval or continously recorded by Roller recorder.

TABLE II

Comparison of Models

From the Standpoint of Assumptions and Approximations Required

Property	Electrolytic Model	Potentiometric Model	Electrical Analyzer
Dimensions of Flow	Two dimensional	Two dimensional	Two or three dimensional.
Variation of density, ρ, with time at any point.	No variation with time.	No variation with time.	May vary with time according to the relation.
Variation of density, ρ, with position	ω nsidered a function of p. varies with p. Therefore included in potential function ϕ .	considered a function of p. varies with p. Therefore included in potential function. ϕ.	considered independent of position throughout a small finite block. Use , ρ_{av}, corresponding to P of block. May vary between blocks.
Variation of viscosity, μ, with psition.	May be considered a function of p and included in the potential function or considered to be part of resistance. In this case corrections are applied to model contours to account for variations.	May be considered a function of p and included in the potential function or considered part of resistance.	Considered constant over the finite block and evaluated as part of the resistance.
Variation of viscosity, μ, with time at a point	No variation with time.	No variation with time.	Not normally considered variable with time. In case of R.C. network, it is possible to alter resistances, to account for this variation.

TABLE II Continued

Change of phase of fluid flowing at a point.	Implies a change of density, viscosity, relative permeability, and porosity, with time. Cannot be dealt with by this model.	Cannot be handled by this model, must assume average properties of two phases at such points.	In the surrounding aquifer, water may be given its true properties. In the initial gas gap, gas may be given its true properties. In sections to be invaded, corrections to R and C could be accomplished by altering their value with time, thus accounting for phase changes, within the block.
Change of permeability, k, with position.	Model contoured to account for variations in permeability.	Model contoured for permeability variations in x and y directions. Vertical variations may be accounted for by parallel flow.	Average permeability given to each block. Value of resistance determined from this.
Change of porosity, f, with position.	Cannot be taken into account.	Can be accounted for when considering the line integral along a flow line. Different values may be used over different sections of the line.	Can be accounted for by altering the average value used for each block.
Gravity	Effects of gravity ignored.	Effects of gravity ignored.	Effects of gravity generally ignored. Theoretically possible to include effects for three dimensional model.

Field of Application of the Model

The selection of a model type, to aid in the solution of a problem, depends upon the nature of the problem under consideration. If the problem is mainly concerned with the movement of fluid in the reservoir, while changes with time are of secondary interest, the potentiometric model, will be applicable. If the problem is mainly concerned with changes in the variables, dependent upon time, the electrical analyzer is the logical choice. A list of the more common types of problems, together with the applicability of each model is given in Table III.

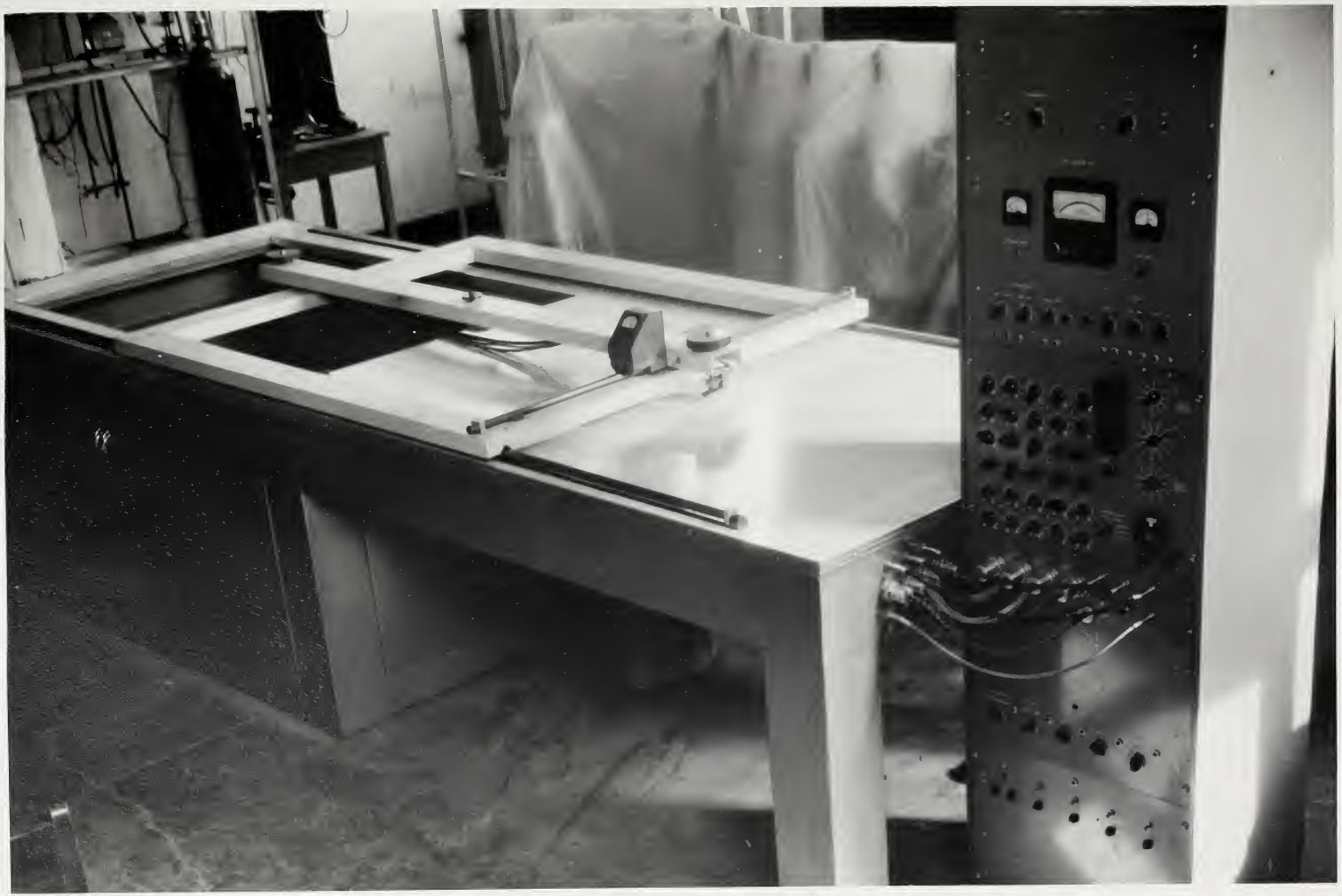
TABLE III

Comparison of Equipment from Standpoint of Applications

Applications	Electrolytic Model	Potentiometric Model	Electrical Analyzer
Gas Recycling Problems	In some cases, cannot deal with large area.	Good solution may be obtained.	Not generally applicable.
Natural Water flooding	Difficult to deal with by this model.	Can be applied if pressure reduction can be ignored, i.e. pressure reduction negligible or uniform throughout field.	Used when natural flooding not sufficient to maintain steady pressure conditions.
Injection Water Flooding.	Can be used if pressure may be considered constant.	Can be applied if pressure may be considered constant.	Used when injection is not sufficient to maintain steady state conditions.
Gas Cap Drive	Not applicable	Not very useful except for preliminary pressure distribution study.	Model can deal with this problem.
Lease Line migration problems and determination of well drainage a areas.	Can be used to solve this problem.	Can be used to solve this problem.	Difficult to apply to this problem.
Gas Solution Reservoir	Not applicable	Not applicable except for preliminary pressure distribution study.	Model can deal with this problem. Switch on gas drive unit, after pressure decline.

A comparison of the three types of electrical models in their present state of development, leads to the following general conclusions.

1. The Electrolytic and Potentiometric models are directly competing types, due to the fact that they both start from the same set of assumptions and are applied to the solutions of the same problems.
2. The chief advantage of the Electrolytic model is the ease with which its results are interpreted, compared to the Potentiometric Model.
3. The chief disadvantage of the Electrolytic model is its relatively limited field of application due to its limited dimensions, and the fact that in areas of low potential gradient, the results are obscured by molecular diffusion.
4. It may be concluded that the potentiometric model employing the four-probe array, is the better choice between these two. This model can be adjusted to solve any problem in two dimensional steady state flow.
5. The Electrical Analyzer is primarily designed for the solution of unsteady state flow. Hence, in general problems that can be solved by means of the potentiometric method, are problems that would be difficult to solve by means of the Electric Analyzer.
6. The two models are complementary in nature, and the specific problem to be solved will normally dictate which analogy is to be used.



IV. DESIGN AND CONSTRUCTION OF THE POTENTIOMETRIC MODEL

Selection of the Model Type

The potentiometric model was selected because it is versatile in its application, and at the same time is of relatively simple construction. The potentiometric model employing the four probe array, will handle a greater variety of problems than the migrating ion type, which is limited by the excessive voltages required for large sized models.

The real choice in models lay between the potentiometric type and the electric analyzer. The electric analyzer is undoubtedly the more versatile model, but its greater complexity indicated that the potentiometric model would be the better starting point. The experience gained in the present study, indicates that any attempt to build an electric analyzer as a graduate research project would be best accomplished as a joint undertaking of several graduates.

(i) Block Diagram of Potentiometric Model

A simplified block diagram of the potentiometric model as developed during this study is shown in Figure (2). The model is seen to consist of a conventional power supply unit, supplying D. C. power of various voltages to the remaining circuits of the model, an oscillator, supplying audio frequency signals to the pool, and other circuits, two null indicators, which receive error signals from the 4 probe array and control the motor units. Motor control circuits which supply power to the balance motors; and a potentiometer, for measuring voltage drops in the pool.

(ii) The Oscillator

It was reported by previous investigators (12)(25) that a dead zone existed at the null point of the response curves of the null detectors used in their models, this was mainly due to the fact they were using 60 cycle

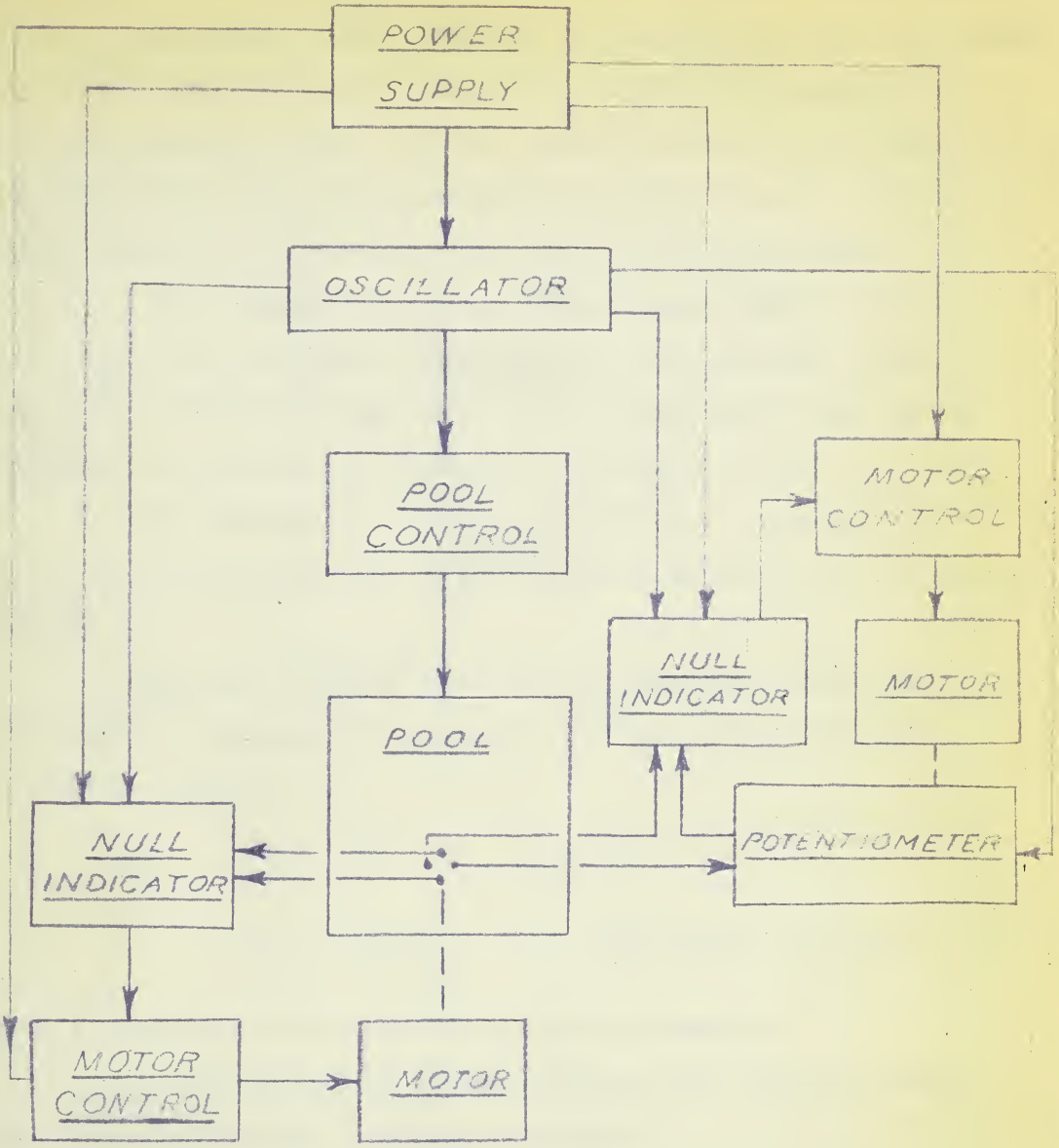


FIG. 2

BLOCK DIAGRAM OF POTENTIOMETRIC MODEL

excitation in the pool unit, and hum in the amplifier tended to mask the null point. It was decided to use a frequency for the pool excitation that differed sufficiently from 60 cycle, that it could be separated from the hum by a frequency sensitive network. The phase sensitive detectors of the null indicator circuits are extremely sensitive to signal frequency, and in effect eleminate all frequencies except that of the received signal.

A second reason for choosing a high frequency signal for the pool voltage, was the effect of polorization at the electrodes. Where polorization effects are lafge, they produce a poor minimum point, and the minimum so obtained does not correspond to the true null point.

This polarization can be controlled either by increasing the surface area of the electrodes, or increasing the frequency of the alternating current.

Kohlrousch & Holburn,[7] state that at a frequency of 1000 cycles polorization is negligible as long as the resistance between electrodes R, obeys the equation.

$$R \geq \frac{50}{A}$$ (for Platinized electrodes)

$$R \geq \frac{2500}{A}$$ (for bright electrodes).

where A is the area of one electrode in square centimeters.

A later investigator, Parker,[7] discovered that electrode spacing also affected polorization and gives the expression.

$$R \geq \frac{160\sqrt{d}}{A}$$ (for Platinized electrodes)

but does not quote an equation for bright electrodes as used in the present study.

It is also realized that with increased frequency, the losses due to stray inductance and capacitance increase, and these losses cannot be accurately predicted. With the relatively large spacing and small area of the electrodes to be used, in the model, it was decided that a frequency of about 400 cycles would be a suitable compromise. This frequency is easy to separate from the 60 cycle hum, and the null points are sharp, indicating that polarization is not excessive.

For the above reasons, a conventional resistance, capacitance, coupled audio oscillator was designed, with a variable frequency between 200 and 400 cycles/second.

This oscillator is connected to two power amplifier stages as shown in Fig. (3).

The oscillator and pre amplifier are of conventional design. The driver stages each consist of a 6 V 6 tube, triode connected, and transformer coupled to the output stage, which consists of two 6 B 4 tubes operating as a Class A - push-pull amplifier. The null detector output is obtained from two transformers, their primaries in parallel, and their secondaries in series. The potentiometer voltage is obtained from a separate transformer whose primary is in parallel with the two supplying the null indicators.

A suggested modification to this circuit is the removal of the potentiometer gain control from its present location, since it has been found that the null indicators require this control to be set near maximum. It is possible to obtain independent control of potentiometer voltage by adding another triode, obtaining its signal from the pre-amp stage, and supplying the potentiometer.

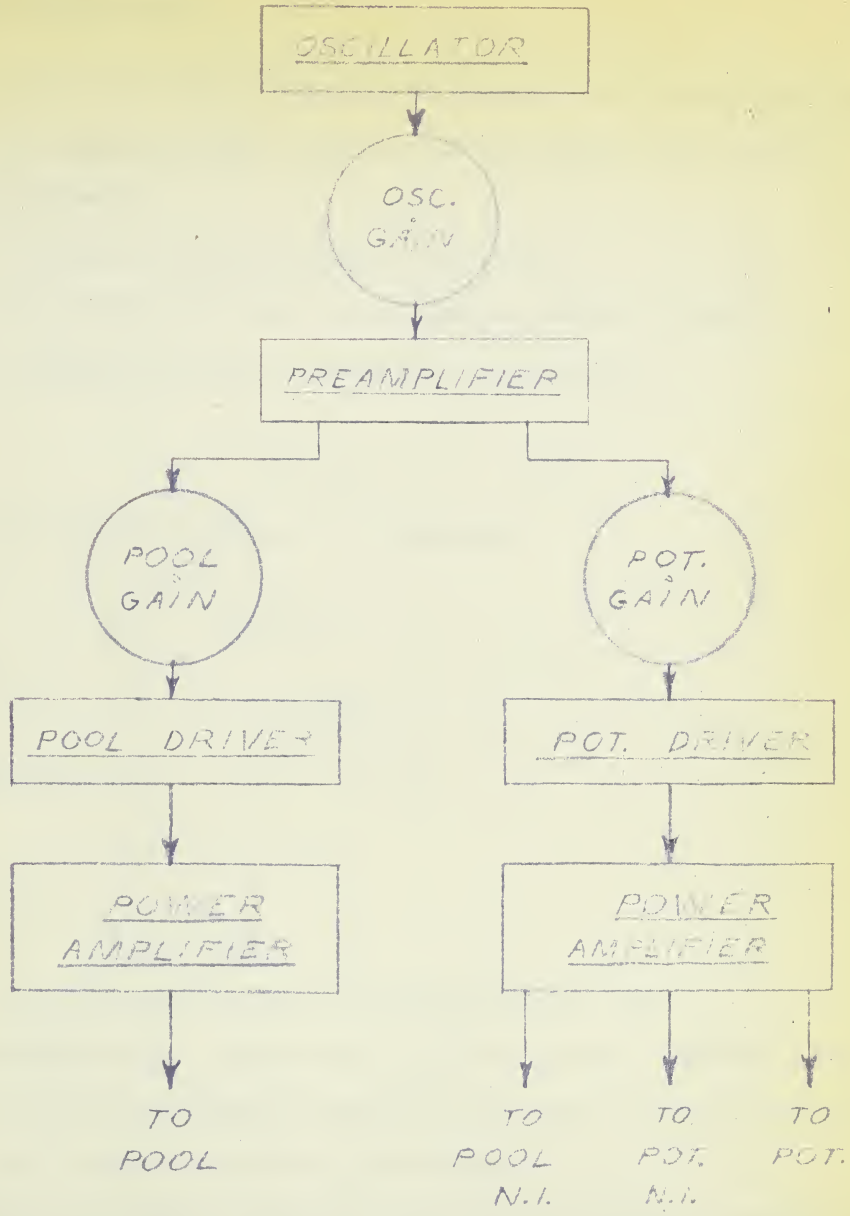


FIG. 3

BLOCK DIAGRAM OF OSCILLATOR UNIT

(iii) The Potentiometer

The potentiometer employed in this model is of a more unorthodox design, the compenents being variable condensers rather than variable resistance elements.

The basis circuit is shown in Fig. #(4).

It is seen, that with the multiplying switch in position 1, then the voltage, E_2 across, C_2, is given by the expression:

$$E_2 = E_1 \frac{Z_{C_1}}{Z_{C_2} + Z_{C_1}}$$

substituting for the impendance of a condencer.

$$Z_C = \frac{1}{2\pi f C}$$

we obtain:

$$E_2 = E_1 \frac{\frac{1}{2\pi f C_1}}{\frac{1}{2\pi f C_1} + \frac{1}{2\pi f C_2}}$$

which simplifies to:

$$E_2 = E_1 \frac{C_2}{C_1 + C_2}$$

or

$$\frac{1}{E_2} = \frac{C_1}{E_1 C_2} + \frac{1}{E_1}$$

When E_1 and C_2 are constant this expression indicates that, $\frac{1}{E_2}$, varies linearly with C_1. In the model, C_1, is a variable condenser, whose capacity is linear with angular position of the rotor, and the potentiometer circuit thus produces a linear scale with respect to $\frac{1}{E_2}$.
This satisfies the design requirement, that the potentiometer be capable of evaluating the expression:

$$t \propto \sum \frac{1}{\Delta E_2}$$

which occurs in the equation for the transit time of a particle along a flow line,

$$t = \frac{a^2}{F} \cdot \frac{\rho f}{R} (\Delta S')^2 \cdot \sum \frac{1}{\Delta E_2}$$

$$\frac{C_1 C_2}{(C_1 + C_2)} = C_A$$

$$\frac{C_3 C_4}{(C_3 + C_4)} = C_B$$

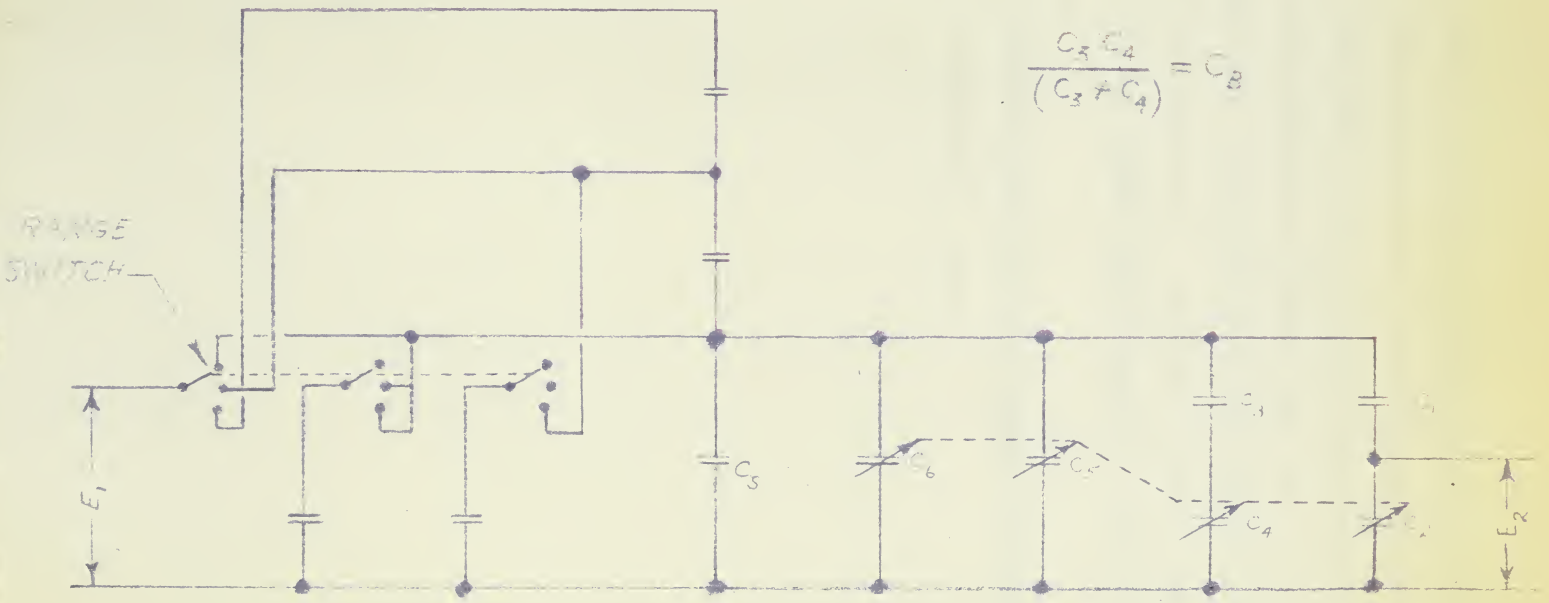


FIG. 4

DIAGRAM OF CAPACITANCE TYPE POTENTIOMETER

The remaining variable and fixed condensers of the network have been added to reduce the variation in the total impedence of the circuit to negligible proportions so that the range-change switch S_1 may function. The computed values presented in Table IV, show that the percent deviation from the average value of the capacity for the network never exceeds a maximum of about one tenth of 1%. This will produce a deviation of one hundredth of 1% in the voltage applied across C_1, and C_2, when the multiplying shunt is in use.

This inherent inaccuracy was considered negligible for the uses to which this model will be put.

TABLE IV

Relationship between Capacity and Angular Position of Variable Condensers in Potentiometer

θ-%	0	10	20	30	40	50	60	70	80	90	100
C_1	60	159	258	357	456	555	654	753	852	951	1050
$\frac{1}{C_1}$	.0167	.00629	.00388	.00280	.00219	.00180	.00153	.00133	.00117	.00105	.00095
$\frac{1}{C_2}$	.0220	.0200	.0200	.0200	.0200	.0200	.0200	.0200	.0202	.0200	.0200
$\frac{1}{C_1}+\frac{1}{C_2}$	.03667	.02629	.02388	.02280	.02219	.02180	.02153	.02153	.02117	.02105	.02095
C_A	27.27	38.04	41.88	43.86	45.07	45.87	46.45	46.88	47.24	47.51	47.73
C_B	47.37	47.51	47.24	46.88	46.45	45.87	45.07	43.86	41.88	38.04	27.27
C_A+C_B	75.00	85.55	89.12	90.74	91.52	91.75	91.52	90.74	89.12	85.55	75.00
C_5	50.00	39.60	32.20	26.60	22.40	19.10	16.50	14.40	12.70	11.20	10.00
C_6	10.00	11.20	12.70	14.40	16.50	19.10	22.40	26.60	32.20	39.60	50.00
$C_A+C_B+C_5+C_6$	135.00	139.25	138.02	136.14	134.92	134.94	134.92	136.14	138.02	139.25	135.00
$\frac{C_1+C_2}{C_2}$	2.200	4.180	6.160	8.14	10.12	12.10	14.08	16.06	18.04	20.02	22.00
$\frac{1}{V_2}$	1.000	1.90	2.80	3.70	4.60	5.50	6.40	7.300	8.20	9.10	10.0
C_{AV}	137.07	137.07	137.07	137.07	137.07	137.07	137.07	137.07	137.07	137.07	137.07
C_S	1863	1863	1863	1863	1863	1863	1863	1863	1863	1863	1863
C_T	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
DEVIATION	2.07	2.18	0.95	0.93	2.15	2.13	2.15	0.93	0.95	2.18	2.07
% DEVIATION	0.104	.109	.0048	.0047	.108	.107	.108	.0046	.0048	.109	.104

The variable condensers are so geared together that the numerical values of C_1, C_3, C_5, and C_6 are related to angular position, in the manner shown in Table IV. The condensers are in turn geared to rotating dials which indicate reciprocal volts on a linear scale over the range 1 to 10. The multiplying switch gives three ranges X1, X10, and X100. The potentiometer as designed is therefore capable of measuring voltages with one thousand fold variation.

The variable condensers and rotating scale are driven by a phase sensitive induction motor, which balances the potentiometer, and is itself controlled by the null indicator - controller.

An overrange protection is supplied by a stop switch, mounted on the dial shaft which actuates a reversing relay when the end of scale travel is reached. The balance motor will therefore cycle at the end of the potentiometer travel until the range change switch is operated.

When an alternating current potentiometer is used, it is necessary to provide for adjustment of the potentiometer voltage phase, to coincide with the phase of the voltage to be measured. For this purpose a phase shift network is provided to alter the potentiometer phase as required.

To calibrate the potentiometer, a thermocouple voltmeter with an accuracy of 0.5% is provided and connected to measure the applied voltage across the potentiometer circuit. It has been noted that this voltmeter, to some extent, alters the applied voltage when switched into the circuit. It is suggested that a shunt resistance equal to the voltmeter resistance be installed, to be used when the voltmeter is not connected in the circuit.

It has also been noted, that the present input circuit of the null detector does not produce a true potentiometric action, and actually loads the potentiometer to some extent at balance. The net effect of this loading action,

is to reduce the span of the potentiometer from the theoretical one to ten reciprocal volts to an actual span of approximately one to eight reciprocal volts.

For the purpose of the preliminary tests, this error was absorbed in the arbitrary scale factor, and the gap in the potentiometer scale between 8 and 10 was covered by halving the voltage applied to the potentiometer and in effect introducing a subsidiary range change equal to X5. This expedient is recognized as temporary, and the trouble should be corrected, either by increasing the size of the potentiometer variable condenser or by redesigning the null indicator input circuit to obtain a closer approach to an infinite impedence at this point.

IV The Null Indicator

The null indicator circuit was designed to have a high impedence input circuit; the ability to separate a small error signal from a large common mode signal; the ability to detect the phase of the error signal; the ability to separate the required signal from extraneous hum; and sufficient output voltage to control the phase sensitive motors, and operate a control relay.

A simplified block diagram of the null indicator is presented in Figure (5)

The input stage, or differential detector was developed by Mathew Conrad.[6] The details of this circuit are shown in Figure #(6).

It is desired that the input stage be responsive to an error signal but should give zero output, whenever, Δe, is zero, even though a large common-mode signal, e, , exists between each of the grid inputs and ground.

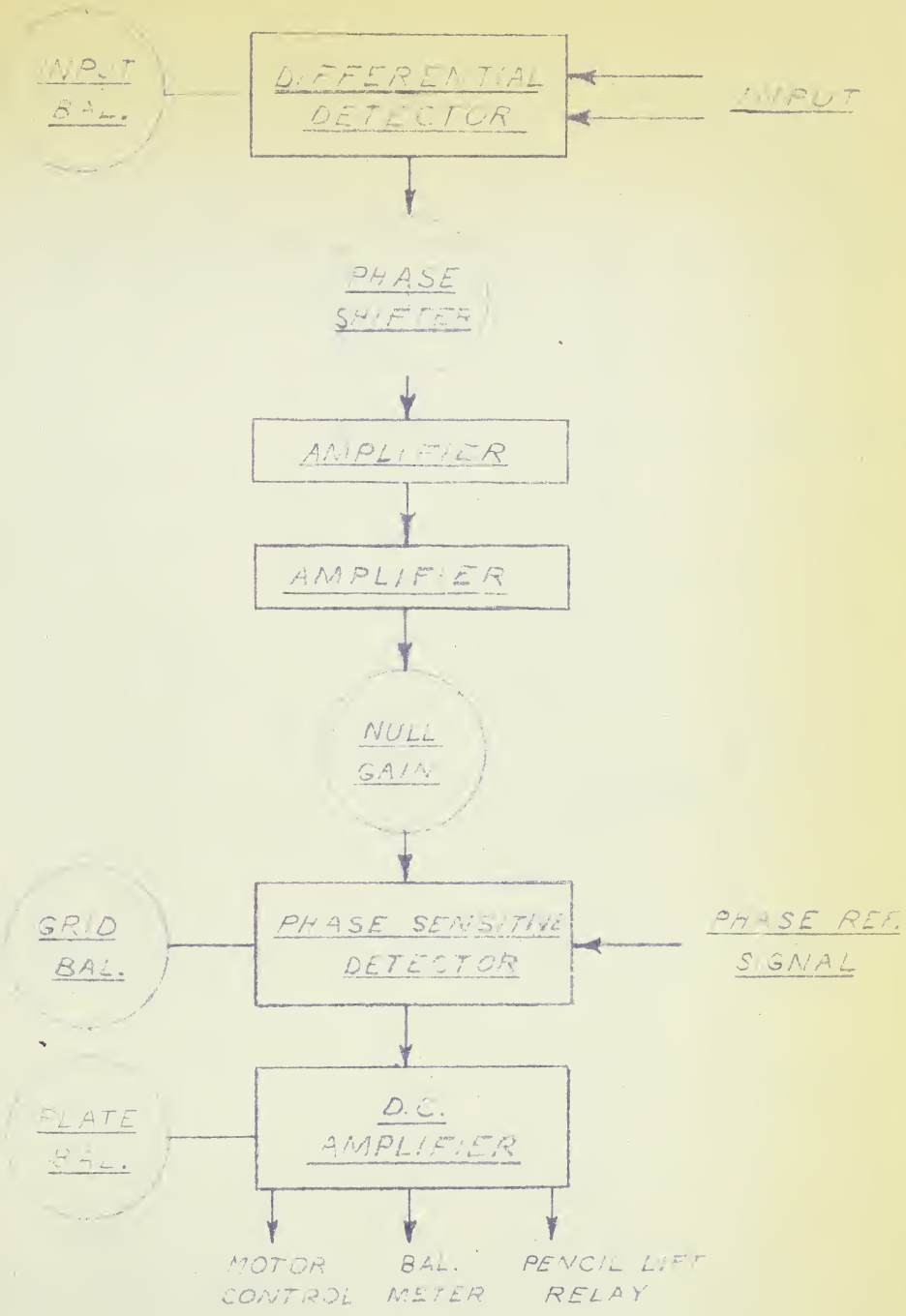


FIG. 5

BLOCK DIAGRAM OF NULL INDICATOR

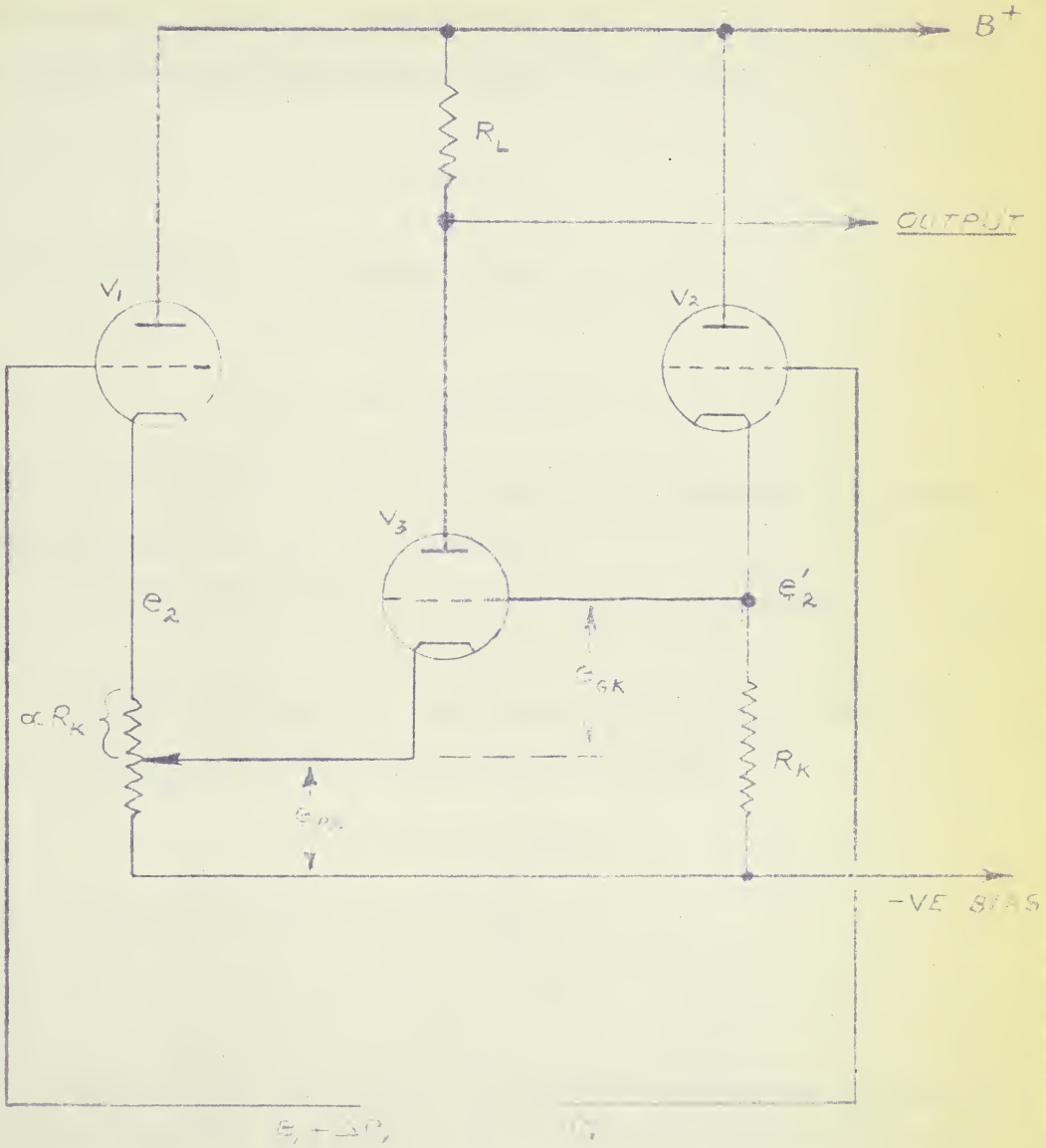


FIG. 6

SIMPLIFIED DIAGRAM OF DIFFERENTIAL DETECTOR

The operation of the circuit is as follows. Assume that equal signals are applied to both input grids (Δe is zero) and assume for the moment that there is no signal in the plate or cathode circuit of V_3. Then equal voltages, e_2, and, e_2', appear at the grids of V_1 and V_2. Now consider V_3; in series with the plate-cathode circuit is the voltage,

$$e_{PK} = (1-a)\, e_2$$

while the effective grid to cathode voltage, e_{GK}, is

$$e_{GK} = e_2' - e_{PK}$$

$$e_{GK} = e_2' - (1-a)\, e_2$$

$$e_{GK} = a\, e_2$$

where "a" is the fractional portion of the cathode load resistor of V_1, above the tap and whose value is to be determined.

For the plate current of V_3 to be constant the relation

$$\mu\, e_{GK} = e_{PK}$$

must be satisfied, where, μ, is the amplification factor of V_3. Substituting for, e_{GK}, and, e_{PK}, the following expression is obtained.

$$\mu\, a\, e_2 = (1-a)\, e_2 ,$$

which on solving for "a" gives the expression:

$$a = \frac{1}{1+\mu}$$

Thus, if the tap in the load resistor is adjusted to satisfy this relationship, the original assumption of no signal in V_3 is justified, assuming linear tube characteristics.

The response of the amplifier to differential signals (Δe not zero) is more difficult to analyze. It is seen that V_1 and V_2 drive the grid and

and cathode of V_3 in opposite directions, thus applying a portion of, Δe, between grid and cathode of V_3. There is some feedback between V_1 and V_3 and the net result is an output for, Δe, signals roughly of the order that would be obtained using V_3 as a simple amplifier.

With this circuit it is possible to amplify a, Δe, signal between zero and five millivolts, with no interference from a common mode signal as high as four volts.

The phase shifter is a conventional phase splitter followed by a resistance capacitance variable phase shift network. This circuit was added to the null detector in order to correct the phase relation between the received signal and the phase reference voltage, and at present is only installed in the potentiometer null detector. The phase shifter is followed by two stages of amplification which are quite conventional and require no explanation.

The phase sensitive detector is intended to detect the phase of the incoming signal and convert it to a D.C. voltage which increases with an increase in amplitude of an "in phase" signal and decreases with an increase in amplitude of an "out of phase" signal.

The basic circuit of the phase detector[25] is shown in Fig. (7). In this circuit, the plates of V_1 and V_2 are supplied with an A.C. voltage of the same frequency as the incoming signal, through a centre tapped transformer. Assume that the input signal is in phase with the plate voltage of V_1. Then, when the grid signal swings positive V_1 will conduct while V_2 having a negative plate voltage will not. On the negative half cycle of the input signal neither tube will conduct. The net effect of this action is that point A of the bleeder A B is held at a negative potential by the charge on condenser C_1, since the full negative voltage is applied across the load resistor R L. While the positive half cycle is dropped by the plate current

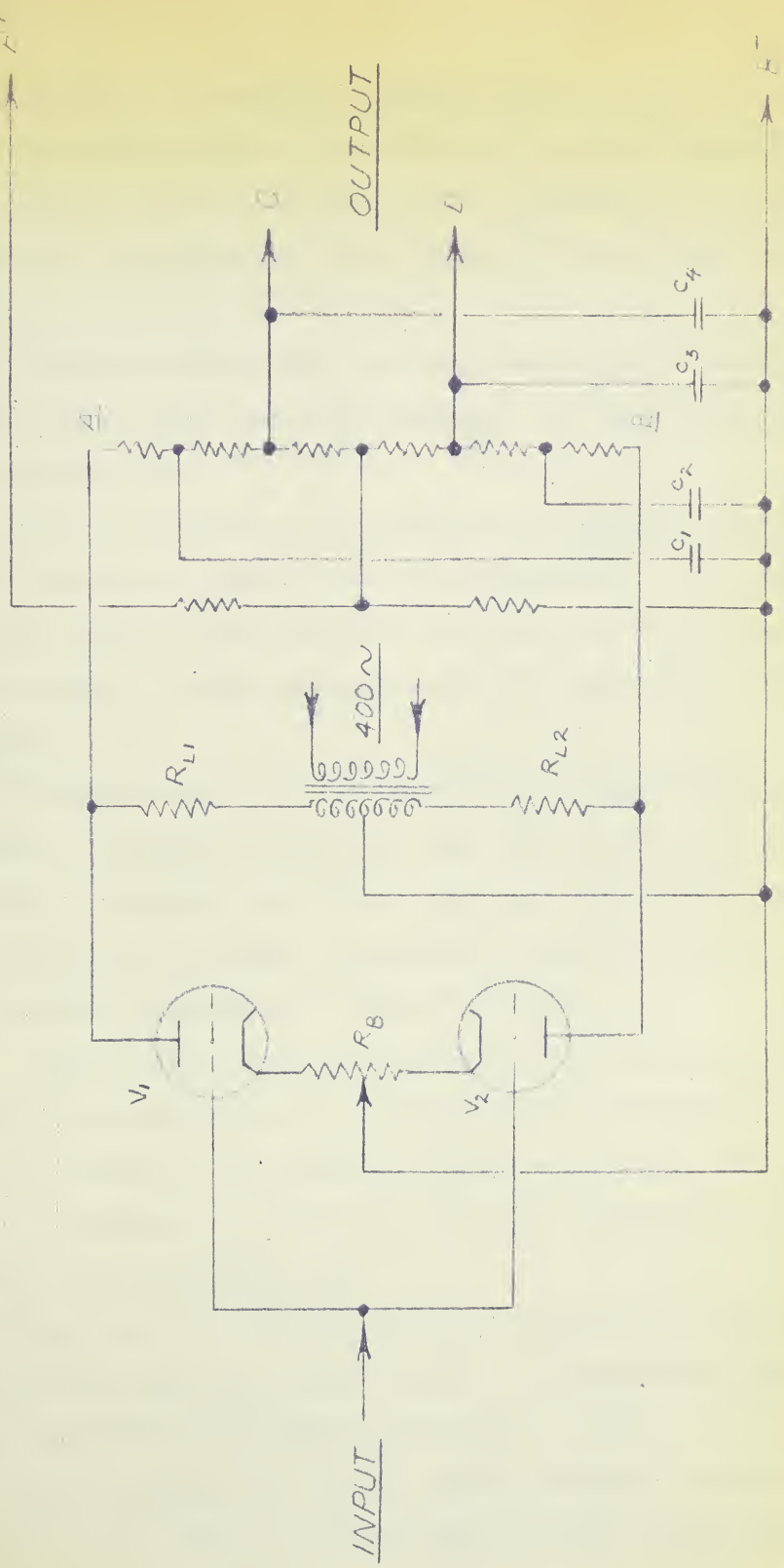


FIG. 7

CIRCUIT DIAGRAM OF PHASE DETECTOR

flowing through R_L. The remaining condensers filter out the A.C. signal and Point C is maintained at a steady voltage below that of point D.

When the phase of the input signal is reversed, the action described above is reversed and point C attains a voltage higher than point D.

The balance control "RB" is adjusted so that at zero signal, the potentials of the points C and D are identical. The phase sensitive detector is then ready for use.

The D. C. amplifier is of conventional "push-pull" design, and produces a variation in output potential of approximately twenty volts, between null and full scale deflection. This variation in potential is used to operate a balance meter, a pencil-lift relay, and the motor control unit.

The balance meter is a milliameter with a range of zero to 5 milliamperes. The torsion springs have been reset to place the zero point at mid scale. Deviations from null are thus registered by deflections on either side of this zero point. A resistor in series with the meter limits current flow to 2 milliamperes at maximum deflection.

Two such output meters are provided, one mounted on the front panel of the null indicator unit, the other mounted on the head of the pantograph. Switches at each metering station permit either meter to be connected to either null indicator, thus allowing the operator to monitor the action of both circuits at will.

The pencil lift relay, is operated in parallel with the null meters, and it in turn controls the current to a solenoid which lifts the plotting pencil when the indicator is off null.

The remaining output also in parallel, is used to drive the motor control unit. It is to be noted that all output voltages of the D.C. amplifier are at a reference potential of plus 150 volts with

respect to ground.

V. The Motor Control Unit

This circuit was designed to supply sixty cycle power to the phase sensitive balancing motors, and to rotate the motors in such a fashion that the error signal received by the null indicators would decrease to zero. At which point the motors would stop rotating. It was originally intended to use a power control circuit similar to that in use on the Brown Instrument Company's "Electronic Potentiometer" but the nature of the input signal necessitated major modifications. The basic circuit as finally evolved is shown in Figure (8).

It will be noted that the Cathodes of V_1 and V_2 are returned to a bleeder network which maintains the cathodes at approximately 160 volts positive. When A and B are at the same potential, approximately 150 volts, that is, the circuit is at null, both V_1 and V_2 are biased almost to "cut-off", and only a small ripple of 120 cycles is passed through the motors. This has no driving action, and the motor remains stationary.

When Point A becomes more positive due to an unbalance in the circuit, point B becomes less positive. Under these conditions V_1 will conduct on the positive half cycle of the plate voltage from transformer T_1, and will develop an A.C. voltage across the high impendance choke L_1. In Parallel with L_1 is the motor circuit consisting of the condenser C_1, the motor control winding and condenser C_2. It was decided to connect the motor in this fashion to avoid the presence of high voltage D.C. in the motor winding.

The second winding of the motor is connected to the A.C. mains and is fully excited at all times. The condensers C_1 and C_2 in series,

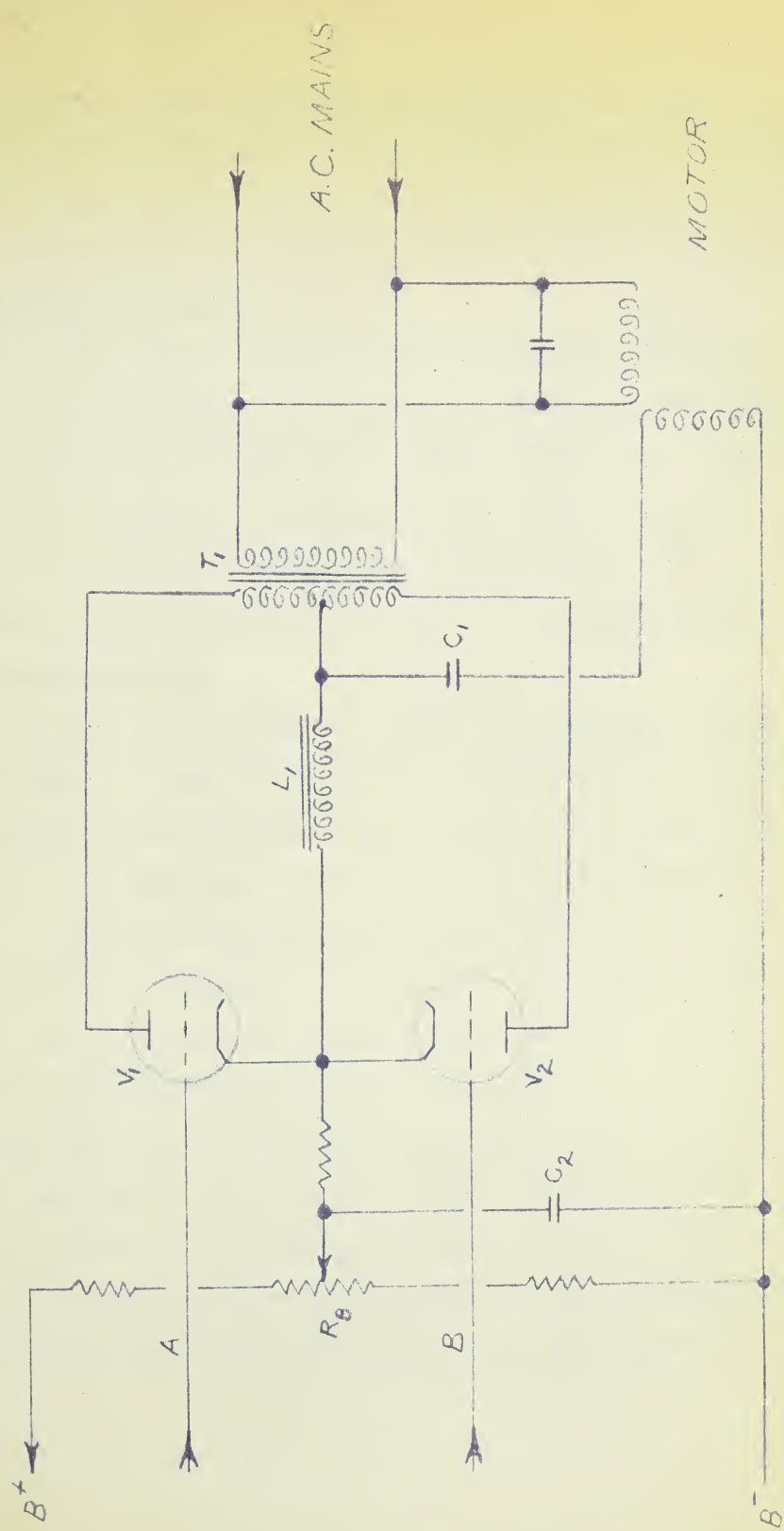


FIG. 8

BASIC CIRCUIT OF MOTOR CONTROL UNIT

with the motor control winding produce sufficient phase shift to operate the motor as a split phase induction motor. When the voltages on points A and B are reversed V_2 will conduct instead of V_1, this reverses the phase of the current through L_1 and the motor control circuit, reversing the direction of the motor.

This circuit therefore fulfills the functions specified in the design. It is suggested that a small direct current passing through the motor winding would assist in damping the control system. This could be accomplished by placing a resistence in parallel with C_1. It is recommended that this modification be carried out on the pool motor control circuit as the tendency of this system to cycle or "hunt" is at times excessive.

VI Pool Control Unit

This unit is designed to act as the centralized control system of the model. It consists of controls, regulating the currents to the pool electrodes; switches regulating the use of the search probes; and other auxilliary controls whose action will be discussed separately.

The power to the pool unit is supplied from one output circuit of the oscillator. This output is connected to two buss-bars in the control unit. One buss distributes current through twenty 100 ohm current measuring resistors, through twenty variable control resistors, to the pool unit terminal strip, where the current is available for the output wells of the model. The second buss distributes current through ten current resistors and control resistors to the pool unit to provide current for the input electrodes. A bank of three selector switches permits the potentiometer to measure the voltage drop across the current resistors and hence measure the current,

The remaining section of the table is used as the recording or plotting area. The pantograph permits direct recording of flow lines or isopotentials as determined in the pool.

The pantograph consists of a carriage running on tracks the length of the table and a tee-square on tracks running across the carriage. One end of the tee square carries the 4 probe search array in the pool, while the other end carries the reference point and plotting pencil. These two rotating elements are joined by a cable drive wrapped around the pulleys and travelling in a helical groove. This wrap construction of the pulleys prevents slippage and assures that the angular relation between elements remains constant. The balance motor, mounted in the centre of the tee square is connected to the rotating elements by a conventional cable drive.

The cables supplying electrical connections to the probes, motor, balance, meter, and solenoid are threaded through weighted pulleys to prevent the slack from interferring with the model's operation.

The cables are then brought up through the table over rollers and connected to the moving carriage. The cable between the carriage and tee square are carried over a spring-loaded roller which removes the slack from this section of the cables and still permits full motion of the tee square.

The weighted cables cause the carriage to roll slightly toward the centre of travel. This action is objectionable and may be cured by the installation of a cable drive to the carriage and tee square, so that these elements will remain in a fixed location during the operation of the model.

(C) Theory of Operation of the Model

(i) General Functions of the Model

The chief function of the potentiometric model, is the duplication and analysis of a desired flow pattern from such information as may be available concerning the physical nature of an oil reservoir, its production rate, and its sources of energy. The accuracy of the results of any model study are naturally limited by the extent and accuracy of the available information.

The physical shape of the reservoir, and the variations in permeability encountered within it, are built into the reservoir model, by means of contours made proportional to the permeability depth product of the oil bearing formation. This contouring should be as detailed as the available geological information permits.

The well locations are marked by the insertion of electrodes representing these wells, and any natural drive in the reservoir must be represented by shaped electrodes, such that the input energy originating from this source generates the correct flow conditions.

When the model has been thus constructed, the available information concerning the physical characteristics of the reservoir have been incorporated, and the model in future operation will automatically use this information in establishing the flow pattern.

The reservoir engineer is able to modify this flow pattern by the choice of well locations and the control of flow rates of both injection and output wells. This flow pattern must then be mapped and the resulting invasion pattern obtained before the merits of a particular production method can be evaluated.

The model, previously described, is designed to assist in the

evaluation of this flow pattern. The model is capable of plotting directly, the isopotential, and stream lines, evaluating the potential gradients for each streamline, and determining the flow rate for each well.

(2) Operation of the Model

The action of the model in accomplishing the various functions listed above is best explained by reference to the "function" switch previously described in Section (B) Part (V_i). The first position of this switch marked "Input isopotential," enables the operator to trace isopotential lines, with the "pool reference earth" control as a reference point. In this position, the potentiometer ground, is connected to the centre tap of a variable resistor, connected across the input and output bus-bars of the pool supply. The other side of the potentiometer is connected to what is normally the foreward current probe of the four probe array. The potentiometer thus measures the voltage difference between the pool probe and the center tap of the "reference earth" control.

In operation, the position of the first isopotential to be plotted, is selected arbitrarily, by the operator placing the probe on the desired location. The "reference earth" control is then adjusted until the potentiometer balances near the lower voltage end of its travel. The balance motor, change over switch is then thrown, disconnecting the potentiometer balance motor from the potentiometer motor control, and connecting the pool balance motor in its place. The rear, or locating probe of the 4 probe array is now brought up to occupy the spot previously occupied by the foreward probe. The array will now rotate until the foreward probe is again on the required isopotential line. By repeating the entire line may be plotted. Caution on the part of the operator is required when using this position, as the isopotential line must exist within the arc of the probe, otherwise the motor will continue rotation and damage will result.

Succeeding isopotential lines may be selected in two ways, with constant spacing along some streamline or with constant voltage difference. In the first instance the forward probe is moved to the required location, the balance motor changeover switch is thrown and the potentiometer allowed to come to balance. The potentiometer may be read at this point and the voltage difference between the two isopotential lines determined. The changeover switch is again placed in the isopotential plotting position, and the second line plotted in the same manner as the first.

If a constant voltage difference is required between successive isopotentials, the probe is simply moved until the desired potential is shown on the potentiometer before it is locked in position by the changeover switch in all these measurements it should be borne in mind that the potentiometer readings are given in reciprocal volts, and must be converted to volts.

With succeeding isopotential lines the potentiometer will progress toward the upper end of its voltage range. When this occurs, the probe is placed on the previously located isopotential, and the "reference earth"control is readjusted, until the potentiometer gives a reading at the lower voltage end of the scale. The next isopotential may now be determined as before.

The second position of the "function" switch marked "output isopotential", is similar in action to that previously described, with the exception that the polarity of the potentiometer is reversed, and succeeding isopotentials are obtained, progressing outwards from the output electrodes.

The third position of the "function" switch marked "gradient" is the four probe plotting position. The "earthed" side of the potentiometer is connected to the central or, locating probe of the array, and the other side of the potentiometer is connected to the forward current probe. The potentiometer will now show directly, the reciprocal voltage existing between the probes. The

rotation of the array is under the control of the isopotential probes and will always rotate so that the array is correctly oriented in the pool. This array has an angular freedom of movement of approximately one and one half turns. It is necessary for the operator to examine this array from time to time, to make sure that the balance points used do not overrange this limit. If this does occur, it is only necessary to switch off the pool motor, and rotate the array 360 degrees, to overcome the difficulty.

The fourth position of the "function" switch marked "input M.A" is for the purpose of measuring the current in each input electrode. The earthed side of the potentiometer is connected to the input bus-bar, while the other side is connected through a selector switch to each of the 100 ohm. current measuring resistors in turn. The potentiometer thus measure the potential drop across the resistor and hence the current to the electrode. The current control resistors may be adjusted until the correct value is obtained. In this connection, it is usually more convenient to place the potentiometer at the required value, switch off the motor and adjust the current control until null is registered on the null meter.

The fifth position of the "function" switch marked "output M.A." is similar in nature and performs a duplicate function for the output electrodes.

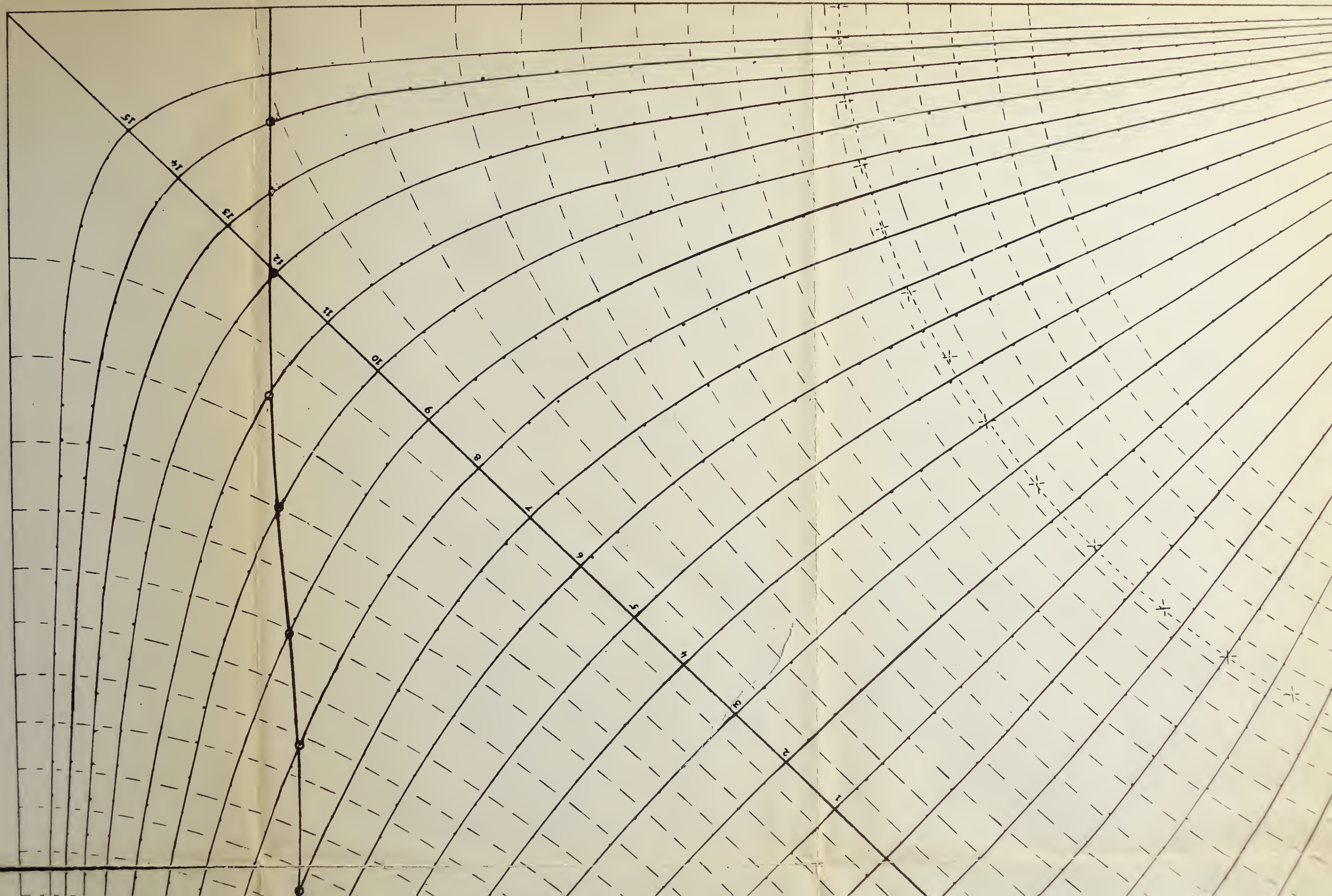
Testing the Model

After construction of the model was completed, its efficiency and precision were tested by performing an analysis of an idealized "five-spot" flood pattern. The pool model consisted of a lucite box twenty inches square containing approximately $3\frac{1}{2}$ inches of electrolyte. The input and output electrodes consisted of lengths of quarter-round brass bar inserted in opposite corners of the pool, with electrical contact being made by means of brass screws passed through the bottom of the tank. The electrolyte consisted of a dilute solution of copper sulphate, sulphuric acid, and ethyl alcohol in water, made up in the following proportions:

15 grams of Copper Sulphate (anhydrous),
5 grams of Sulphuric acid,
5 grams of Ethyl Alcohol,
100 grams of Distilled Water.

This stock solution was diluted with distilled water in the ratio of one part solution to fifty parts of water.

With the model in operation the flow pattern was plotted giving the results shown in Figure 11. In the course of this plotting, the location of the central stream line was first determined, by connecting a thread between the two electrodes, and transfering this line to the plotting paper by means of the locating probe. The model was then switched on and the plotting array placed on this central line. The orientation of the plotting pencil was then adjusted until the balance point of the four probe array coincided with the central line. When this bearing was established, the remaining lines were obtained in the manner previously described, and the potentiometer readings were recorded for each interval along each streamline.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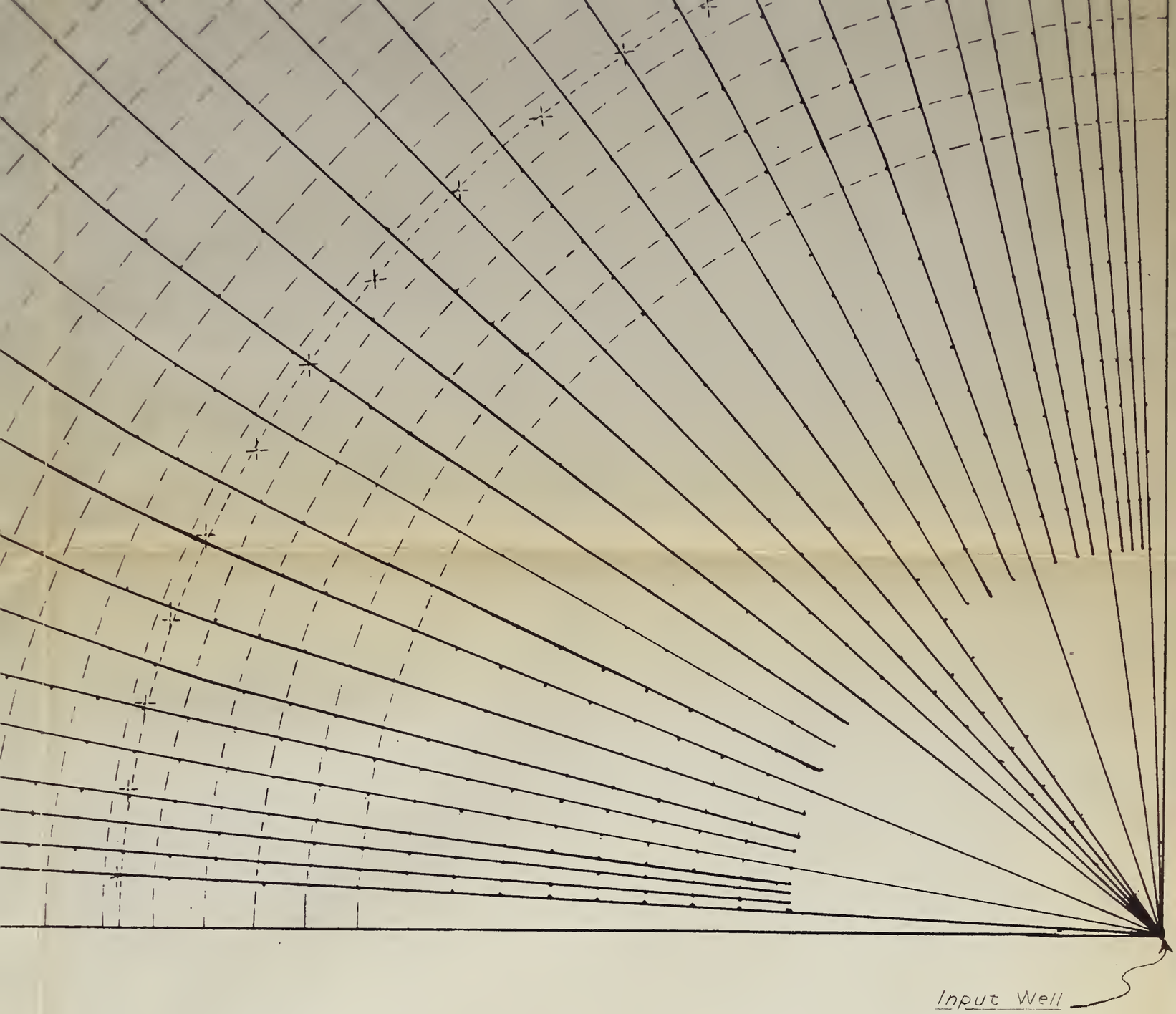


G. 11

UNIVERSITY OF ALBERTA

DEPARTMENT OF CHEMICAL AND PETROLEUM ENGINEERING

POTENTIOMETRIC MODEL

INVASION PATTERN OF IDEALIZED "5 - SPOT FLOOD"

PROGRAM A. OBTAINED DURING PRELIMINARY

STUDY WITH POTENTIOMETRIC MODEL

DATE: APRIL 2 1952 BY: J.J. Mast

Output Well

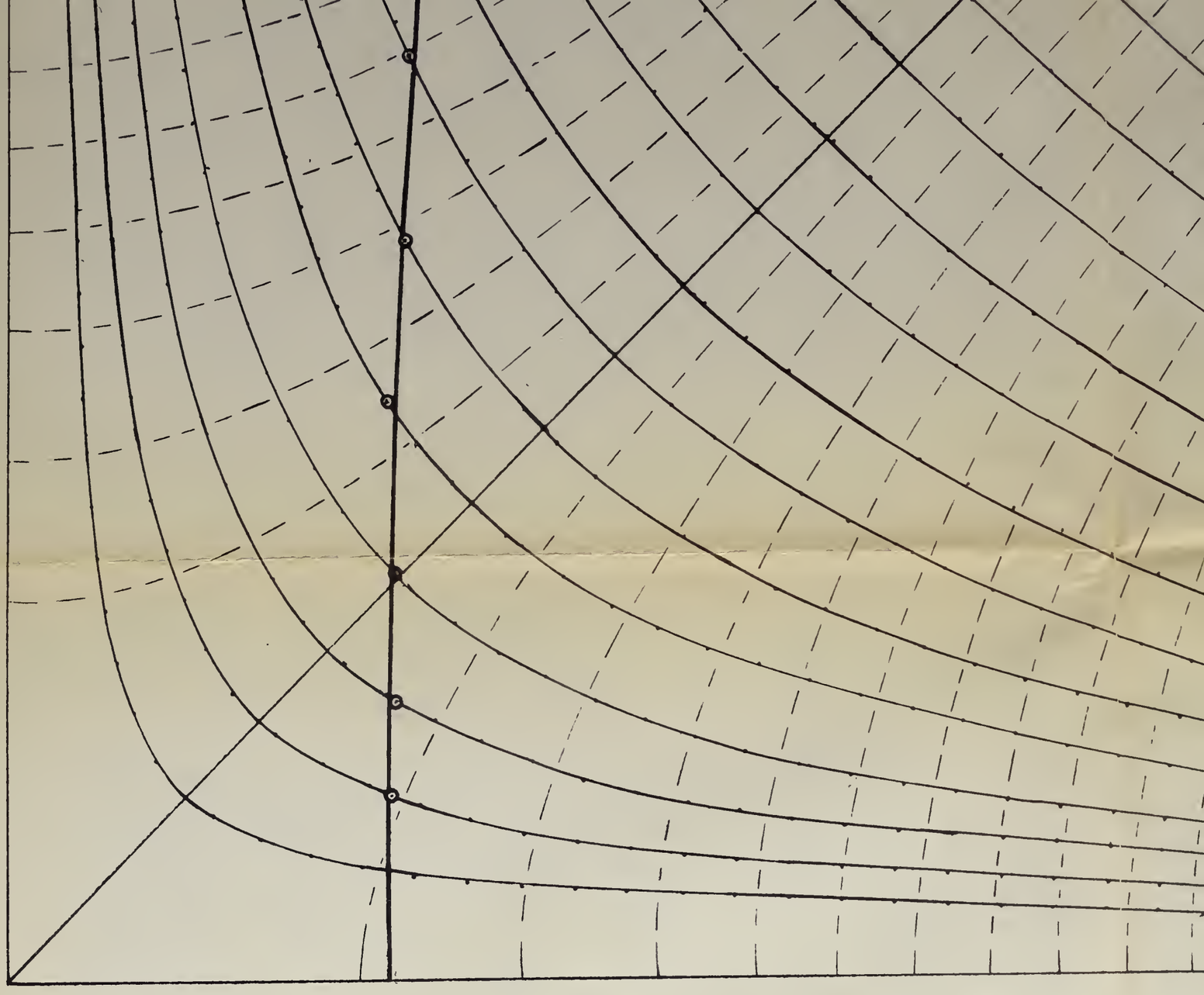


FIG. 11

LEGEND

FLOW LINE ΔS

ISOPOTENTIAL

INTERPOLATED ISOPOTENTIAL

CALCULATED POINTS

FLOOD BOUNDARY

TABLE V

Potentiometer Readings for Flow Lines of "Five Spot" Flood $\frac{1}{\text{Volts}}$

	Streamline Number						
ΔS	1	2	3	4	5	6	7
1	.12	.12	.12	.12	.12	.12	.12
2	.34	.34	.34	.34	.34	.34	.34
3	.56	.56	.56	.56	.56	.56	.56
4	.76	.76	.76	.76	.76	.76	.76
5	.99	.99	.99	.99	.99	.99	.99
6	1.18	1.18	1.18	1.18	1.18	1.18	1.18
7	1.41	1.41	1.41	1.41	1.41	1.41	1.41
8	1.62	1.62	1.62	1.62	1.62	1.62	1.62
9	1.81	1.81	1.81	1.81	1.81	1.81	1.81
10	2.02	2.02	2.02	2.02	2.02	2.02	2.02
11	2.23	2.23	2.23	2.23	2.23	2.23	2.23
12	2.42	2.42	2.42	2.42	2.42	2.42	2.42
13	2.61	2.61	2.61	2.61	2.61	2.61	2.61
14	2.79	2.79	2.79	2.79	2.79	2.79	2.79
15	3.00	3.00	3.00	3.00	3.00	3.00	3.00
16	3.17	3.17	3.17	3.18	3.18	3.20	3.21
17	3.36	3.36	3.36	3.37	3.39	3.41	3.42
18	3.58	3.58	3.58	3.59	3.60	3.65	3.69
19	3.77	3.77	3.77	3.77	3.78	3.82	3.85
20	3.94	3.94	3.94	3.95	3.96	4.04	4.09

TABLE V (Continued)

AS	1	2	3	4	5	6	7
21	4.09	4.09	4.09	4.10	4.10	4.20	4.25
22	4.26	4.26	4.26	4.28	4.31	4.43	4.48
23	4.41	4.41	4.41	4.43	4.49	4.62	4.68
24	4.55	4.55	4.55	4.61	4.67	4.81	4.87
25	4.71	4.72	4.72	4.76	4.85	4.98	5.07
26	4.85	4.87	4.88	4.93	5.00	5.14	5.25
27	4.91	4.93	4.94	5.08	5.15	5.31	5.55
28	5.00	5.07	5.10	5.18	5.28	5.55	5.81
29	5.08	5.14	5.17	5.34	5.44	5.77	6.01
30	5.11	5.19	5.26	5.49	5.62	6.01	6.29
31	5.16	5.36	5.41	5.71	5.79	6.29	6.50
32	2.06 (31.4)	3.33 (31.6)	4.95 (31.9)	5.82	5.99	6.41	6.72
33				1.18 (32.2)	4.26 (32.7)	6.58	6.92
34						2.03 (33.3)	6.31 (33.9)
35							
36							
37							
38							
39							
40							

TABLE V (Continued)

	Streamline Number						
ΔS	8	9	10	11	12	13	14
1	.12	.12	.12	.12	.12	.12	.12
2	.34	.34	.34	.34	.34	.34	.34
3	.56	.56	.56	.56	.56	.56	.56
4	.76	.76	.76	.76	.76	.76	.76
5	.99	.99	.99	.99	.99	.99	.99
6	1.18	1.18	1.18	1.18	1.18	1.18	1.18
7	1.41	1.41	1.41	1.41	1.41	1.41	1.41
8	1.62	1.62	1.62	1.62	1.62	1.62	1.62
9	1.81	1.81	1.81	1.81	1.81	1.81	1.81
10	2.02	2.02	2.02	2.02	2.02	2.02	2.02
11	2.23	2.23	2.23	2.23	2.23	2.23	2.23
12	2.41	2.41	2.41	2.41	2.41	2.41	2.41
13	2.61	2.61	2.61	2.61	2.61	2.61	2.61
14	2.79	2.79	2.79	2.79	2.79	2.79	2.79
15	3.00	3.00	3.00	3.00	3.00	3.00	3.00
16	3.21	3.21	3.21	3.22	3.23	3.23	3.24
17	3.44	3.47	3.48	3.49	3.49	3.49	3.50
18	3.71	3.75	3.75	3.77	3.77	3.78	3.81
19	3.87	3.90	3.91	3.91	3.94	3.96	4.00
20	4.14	4.16	4.17	4.18	4.20	4.23	4.26

TABLE V (Continued)

Streamline Number

ΔS	8	9	10	11	12	13	14
21	4.30	4.34	4.40	4.44	4.45	4.51	4.53
22	4.57	4.59	4.61	4.65	4.69	4.74	4.78
23	4.77	4.82	4.86	4.91	4.96	5.02	5.14
24	5.00	5.04	5.14	5.17	5.27	5.30	5.54
25	5.22	5.28	5.37	5.50	5.55	5.61	5.94
26	5.42	5.52	5.78	5.76	5.85	5.93	6.31
27	5.73	5.81	6.05	6.16	6.22	6.28	6.73
28	6.06	6.17	6.39	6.55	6.61	6.69	7.12
29	6.30	6.54	6.79	6.93	7.03	7.13	7.56
30	6.59	6.94	7.24	7.42	7.50	7.61	8.06
31	6.98	7.07	7.53	7.82	7.96	8.06	8.63
32	7.11	7.28	7.87	8.29	8.36	8.68	9.11
33	7.29	7.54	8.17	8.64	8.75	9.15	9.90
34	7.46	7.73	8.46	9.09	9.26	9.85	10.68
35	5.93 (34.8)	7.91	8.69	9.50	9.97	10.49	11.48
36		4.85 (35.6)	8.88	9.84	10.57	11.18	12.38
37			4.43 (36.5)	10.14	11.21	11.96	13.11
38				4.02 (37.4)	11.61	12.73	13.85
39					7.13 (38.6)	13.29	14.71
40						9.63 (39.7)	15.88
41							9.49 (40.6)

TABLE VI

Determination of $\Sigma \frac{1}{v}$ Along Streamlines

STREAMLINE	ΔS	$\Sigma \frac{1}{v}$	DIFF.	191.74 -	FRACT.	ΔS INPUT	ΔS OUTPUT
2	57.2	191.25	1.18	.35	0.4	57.6	5.6
	58.2	192.43					
3	54.8	190.02	1.81	1.72	0.9	55.7	8.1
	55.8	191.83					
4	52.4	189.80	2.42	1.94	0.8	53.2	11.2
	53.4	192.22					
5	50.4	189.58	3.00	2.16	0.7	51.1	14.3
	51.4	192.58					
6	47.6	190.22	3.82	1.52	0.4	48.0	8.6
	48.6	194.04					
7	45.8	190.81	4.48	0.93	0.2	46.0	21.8
	46.8	195.25					
8	43.6	190.11	5.42	1.63	0.3	43.9	25.7
	44.6	195.53					
9	42.2	189.21	6.54	2.53	0.4	42.6	28.6
	43.2	195.75					
10	40.0	184.42	7.87	0.0	0.0	41.0	32.0
	41.0	191.67					
11	38.8	178.68	13.03	0.0	0.0	39.2	35.0
	39.8	191.71					
12	38.6	186.79	7.13	4.95	0.5	39.0	38.2
	39.2	193.92					
13	38.0	184.38	13.29	7.36	0.6	38.6	
	39.0	197.67					
14	37.0	179.59	13.85	11.15	0.8	37.8	
	38.0	193.44					

The potentiometer readings, in reciprocal volts, are shown in Table V. These readings are proportional to transit time, and their sum will be a measure of the total time required to travel the distance "S" along the streamline. The readings for each flow line were summed with the results shown in Table VI. Using the total transit time for a particle along the central flow line (number One) as a base, the time intervals for each of the remaining streamlines were summed on a progressive total basis until this total equalled the base time. In most cases it was necessary to add a fraction of an interval in order to obtain the equality. The necessary computations, determining the fraction of an interval required to give a total transit time of 191.74 reciprocal volts, were included in Table VI. The required number of, , intervals was then measured off along each flow line to give the invasion pattern shown in Figure 11.

The area not included inside this invasion line was then evaluated by the use of Simpsons Rule and the ratio of flooded area to total area was computed. This ratio is termed the "flooding efficiency" of the invasion pattern and was found to be 71.2% in this problem. The published value for this efficiency is given as 72.3%,[19] which would indicate that the model possess a sufficient degree of accuracy for the problems it is designed to handle.

As a further and more precise check of the model's performance a mathematical analysis of the flow problem was conducted by the Mathematics Department of this University. In the course of this analysis the general equation:

$$P_{(x,y)} \doteq \text{of } \text{Log}_{10}\left\{\frac{[\cosh \pi y - \cos \pi x][\cosh \pi(y-2) - \cos \pi x][\cosh \pi(y+2) - \cos \pi x]}{[\cosh \pi(y-1) + \cos \pi x][\cosh \pi(y+1) + \cos \pi x]}\right\} + C$$

describing the pressure distribution was developed and confirmed the equation as published by M. Muskat. Using this equation, the location of the isopotential line bisecting the side of the unit square was computed. It is of interest to note that in the course of this calculation, the final coordinates of the calculated points are obtained by difference between two numbers which are almost equal. The result is that although the calculations start with "six figure" accuracy, the final coordinates have only "two figure" accuracy, with the second figure open to some doubt. The result of this is a certain amount of "scattering" of the calculated points. The same isopotential line was obtained from the model results by interpolation between two plotted lines. This interpolated line is presented in Figure 11 together with the locations of the calculated points. On examination of this plot it can be seen that the line obtained from the model forms the "best fit" line for the calculated points. This would indicate that the model is capable of plotting isopotential lines with greater accuracy than it is possible to obtain using the six figure exponential tables available, and computing the curve.

It was also considered necessary to evaluate the accuracy of the model while plotting a flow line and evaluating the poential gradient. To accomplish this, the pressure distribution was determined along one flow line, again using the general equation presented above. The pressure or voltage at selected intervals corresponding to ΔS, intervals used in the model, was evaluated assuming an arbitrary voltage ,V, to be applied between two electrodes of radius ΔS. The voltage difference between two ΔS, intervals was then computed and this difference was then divided by the assumed total voltage to obtain the

ratio, $\frac{\Delta V}{V}$, a dimensionless group, from which all arbitrary constants have been removed. This same ratio was computed from the model results, by obtaining the reciprocal of the potentiometer readings for each, ΔS, interval. These voltages were then summed, omitting the voltage drop accross the first, ΔS, interval, to obtain a total voltage corresponding to that used in the mathematical development. Each voltage drop was then divided by the total voltage to give the ratio, $\frac{\Delta V}{V}$, for the model. These calculations are presented in tabular form in Table VII, together with the results obtained from the mathematical analysis. A comparison of the two sets of data is included in the table, and this comparison indicates that the model results check with the calculated results with an average error of less than one percent. The comparison also indicates that the error is random in distribution. This error is at least partly due to the fact that the pantograph was not equipped with a suitable locking device at the time the measurements were made, and a tendency to shift in position while a potentiometer reading was being made, was noted. When the mechanical drive is installed on the pantograph, an improvement in accuracy is to be expected.

TABLE VII

Comparison Between Calculated And Experimental Values of $\frac{\Delta V}{V}$ Measured Along Central Streamline

ΔS	$\frac{1}{\Delta V}$	ΔV	$\frac{\Delta V}{V}$	$\frac{\Delta V}{V}$ CALC.	ERROR	PERCENT ERROR
1	.12					
2	.34	2.941				
3	.56	1.786				
4	.76	1.316				
5	.99	1.010				
6	1.18	0.847	0.0265	0.0268	-.0003	1.12
7	1.41	0.709	0.017			
8	1.62	0.617				
9	1.81	0.552	0.0172	0.0173	-.0001	0.58
10	2.02	0.495				
11	2.23	0.448				
12	2.42	0.413	0.0129	0.0129	.0000	0.00
13	2.61	0.383				
14	2.79	0.358				
15	3.00	0.333	0.01037	0.0103	+.00007	0.69
16	3.17	0.314				
17	3.36	0.298				
18	3.58	0.279	0.00869	0.00864	+.00005	0.58

TABLE VII (Continued)

ΔS	$\frac{1}{\Delta V}$	ΔV	$\frac{\Delta V}{V}$	$\frac{\Delta V}{V}$ CALC.	ERROR	PERCENT ERROR
19	3.77	0.265				
20	3.94	0.254				
21	4.09	0.245	0.00763	0.00757	+.00006	0.79
22	4.26	0.235				
23	4.41	0.227				
24	4.55	0.220	0.00685	0.00685	.00000	0.00
25	4.71	0.213				
26	4.85	0.206				
27	4.91	0.204	0.00636	0.00641	-.00005	0.78
28	5.00	0.200				
29	5.08	0.197				
30	5.11	0.196	0.00612	0.00618	-.00006	0.97
31	5.16	0.194				
31.4	2.06	0.078				
		16.033				
		X2 = 32.066				

VI Conclusions and Recommendations

It was demonstrated in the previous section, that the model's accuracy was within one percent at all times, a figure which is considered adequate for the studies this model is designed to undertake.

The self balancing features incorporated in the model, relieve the operator of much tedious manipulation and speed up the operation considerably. The incorporation, of an integrator to perform the summation of the potentiometer readings, would approximately double the speed of operation. Preliminary examination of the literature indicates that a "straight line" integrator, manufactured by Taylor Instrument Company could be modified to serve this purpose, and would appear to be well worth investigating.

The operation of this machine during the preliminary tests has indicated certain modifications which should be included before the model is considered fully operational. These suggested changes have been indicated earlier, but are summarized here for convenience.

(a) Modification to the Oscillator

The oscillator unit should be modified to provide an independent control of the voltage supply to the potentiometer. This can be accomplished by the incorporation of another triade to be, obtaining its signal from the "pre-amp" stage and driving the potentiometer supply transformer.

(b) Modification of Potentiometer

(i) Include a shunt resistance to replace the voltmeter when not in use, so that the phase shift network has a constant load.

(ii) To overcome the loading effect of the null indicator on the potentiometer span, a larger variable condenser should be provided. This could be accomplished by using the second linear condenser at present used as ballast, in parallel with the measuring condenser. Larger non-linear condensers should then be added in place of the present ones.

(c) Modification of Motor Control Unit.

A resistor in series with the blocking condenser should be added to provide direct current to the motor control winding to assist in the damping of the control circuit.

(d) Modification to Pantograph

A mechanical drive should be added to the pantograph to lock it in position and prevent shippage while a reading is being taken.

(e) Addition of Integrator

The addition of a mechanical integrator would greatly speed up the action of the model. When these modifications have been completed, a satisfactory performance may be expected from the model.

NOMENCLATURE

A - arbitrary scale factor relating model thickness to reservoir thickness.

Ax - gross cross sectional area presented to flow in x direction =

B - arbitrary scale factor relating electrical capacity to reservoir storage capacity.

C_E - electrical capacitance.

c - compressibility factor of reservoir fluid.

D - arbitrary scale factor relating electrical resistance to fluid flow resistance.

E - electrical potential.

F - arbitary scale factor relating electrical potential to reservoir pressure.

f - porosity of pourous medium.

i_x - electrical current component in x direction.

k - permeability of porous medium.

P - pressure at any point in reservoir.

Q_x - volumetric rate of fluid flow in x direction.

R - Gas constant

R_E - electrical resistance

R_F - fluid resistance

T - reservoir absolute temperature.

t - time - for reservoir.

t' - time - for model.

V_o - gross volume of reservoir.

$(Vof)_G$ - available volume in reservoir occupied by gas.

$(Vof)_L$ - available volume in reservoir occupied by liquid.

NOMENCLATURE (Continued)

v_G - specific volume of gas in reservoir.

v_x-v_y-v_z - linear velocity components of fluid.

x, y, z - linear dimensions of reservoir.

x' y' z' - linear dimensions of model.

Z - compressibility factor of reservoir gas.

μ - viscosity of fluid.

ρ - denisty of fluid

σ - specific conductivity of model sheet.

BIBLIOGRAPHY

1. Botset, H. G. "The Electrolytic Model and Its Applications to the Study of Recovery Problems," A.I.M.E. Petroleum Technology, Vol. 166 (1946) p. 15.

2. Botset, H. G. " The Electrical Model and Its Applications," Oil and Gas Journal (1949) March 31.

3. Brownscombe and Collins. "Estimation of Reserves and Water Drive, From Pressure-Production History", A.I.M.E. Pet. Tech., April (1949).

4. Bruce, W. A. "An Electrical Device for Analyzing Oil Reservoir Behaviour," A.I.M.E. Trans., Vol. 151 (1943), p. 112-124.

5. Bruce, W.A. "Oil Pool Analyzer", Oil and Gas Journal, (1946) Vol. 45 (1) p. 90.

6. Conrad, M. "A Differential Amplifier Null Detector," Electronics February 1950.

7. Davies, C.W. The Conductivity of Solutions

8. Horner and Bruce. "Electrical Model Studies of Secondary Recovery," API Prod. Bull. No. 230 (1943) pp. 190-198.

9. Hurst & Van Everdingen. "Flow in Parallel Beds," A.I.M.E. Pet. Tech. Jan. 1946.

10. Hurst and McCarty. "Applications of Electrical Models," API Prod. Proct. (1941) pp. 228-240.

11. Kelton, F. C. "An Electrolytic Model Study of Cycling in Crapeland Field," API Prod. Bull. No. 230 (1943) pp. 199-205.

12. Lee, B. D. "Potentiometric Model Studies of Fluid Flow," A.I.M.E. Pet. Tech., Sept. 1947.

13. Leverett, Lewis and True "Dimensional Model Studies of Oil Field Behavior". A.I.M.E. Trans. Vol. 146, pp. 175-193.

14. Markus, J. "Predictions by Electonics," Scientific American Vol. 176, May 1947.

15. Marshall & Oliver. "Some Uses and Limitation of Model Studies," A.I.M.E. Pet. Tech., Jan. 1947.

16. Miller & Lents, "Economics of Recycling" Oil and Gas Jnl., Mar. 18, 1948.

17. Miller & Lents. "New Methods of Predicting Gas Condensate Reservoir Performances Under Cycling Operations." API Drill. and Prod. Pract. (1945).

18. Muskat M. and Wyckoff. "Artificial Flooding by Water Injection," A.I.M.E. Trans. Vol. 107 (1934).

19. Muskat M. Flow of Homogeneous Fluids. McGraw-Hill Co., (1937).

20. Muskat, M. "Bibliography" Pet. Eng. Vol. 17, Jan. 1946.

21. Muskat, M. Physical Principles of Oil Production McGraw-Hill Co., (1948).

22. Muskat, M. "Gas Injection." Oil and Gas Jnl., Mar. 31, 1949.

23. Muskat, M. "Partial Water Drives, "Oil and Gas Jnl. Apr. 7, 1949.

24. Muskat, M. "Theory of Potentiometric Models," Pet. Tech., Nov. 1948.

25. Redmond, W.P. "Theory and operation of Electric Oil Field Models," Unpublished paper supplied by Courtesy Imperial Oil Ltd.

26. Schaeffer, R. "Extending the Application of the Electric Analogy," Pet. Tech., Jan. 1947.

27. Snedden. "Petroleum Research Goes Electronic" Pet. Eng. Vol. 17, Nov. (1945) P. 57.

28. Swearingen, J.S. "Predicting Wet Gas Recovery in Cycling," Oil Weekly, Dec. 25, 1939, p.30.

29. Taylor & Sharman. "Electrical Analogy for Flow of Compressible Fluids, "Proc. Roy. Soc. London (A) Vol. 121, p. 199

30. Wolf, A. "Electrical Models in Study of Secondary Recovery Projects," Oil and Gas Jnl. April 15, 1948.

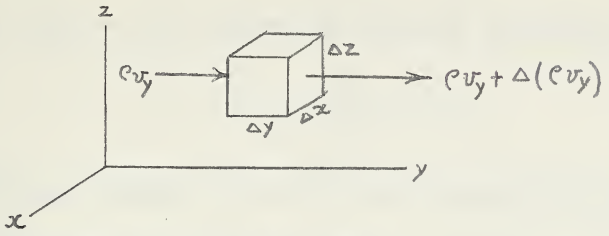
31. Wyckoff, Botset and Muskat, "Mechanics of Porous Flow Applied to Water Flooding," A.I.M.E. Trans. Vol. 103, p. 219-249.

32. Wyckoff and Botset. "An experimental Study of the Motion of Particles in Systems of Complex Potential Distribution", Physics Vol. 5, p. 265 (1934).

33. "Miniature Oil Field Foretalls Production", Petroleum Engineer, Nov. 1945.

Appendix A.

The Equation of Continuity in Fluid Flow



Consider an elemental volume, $\Delta x . \Delta y . \Delta z .$ of a porous medium of poristy, f . Assume that a fluid, with a density, ρ, is entering in the y direction with a velocity v_y. The mass velocity will be the product of these two quantities, ρv_y. The total mass of fluid entering per unit time in the y direction will be

$$\rho v_y \Delta x \Delta z$$

Consider also the fluid leaving the block in the y direction, with a mass velocity

$$\left[\rho v_y + \Delta(\rho v_y)\right].$$

The total mass leaving per unit time in the y direction will be

$$\left[\rho v_y + \Delta(\rho v_y)\right] \Delta x \, \Delta z .$$

The mass increase in the block due to flow in the y direction will be the difference between these two quantities,

$$\rho v_y \Delta x \Delta z - \left[\rho v_y + \Delta(\rho v_y)\right] \Delta x \Delta z ,$$

which on simplifying becomes

$$- \Delta(\rho v_y) \Delta x \Delta z .$$

Similarily, for flow in the x direction, the mass increase is

$$-\Delta(\rho v_x)\,\Delta y.\,\Delta z;$$

while for flow in the z direction the mass increase is

$$-\Delta(\rho v_z)\,\Delta y.\,\Delta x.$$

The total mass increase per unit time is given by the sum of these three quantities and may be written,

$$-\left[\Delta(\rho v_x)\,\Delta y\,\Delta z + \Delta(\rho v_y)\,\Delta x\,\Delta z + \Delta(\rho v_z)\,\Delta x\,\Delta y\right]$$

But, the total mass increase per unit time is also equal to the product of the fluid volume and the change in density per unit time. These two expressions can be equated to give

$$\left[\Delta(\rho v_x)\Delta y\Delta z + \Delta(\rho v_y)\Delta x\,\Delta z + \Delta(\rho v_z)\Delta x\,\Delta y\right] = -\Delta x\,\Delta y\,\Delta z\,f\,\frac{\Delta\rho}{\Delta t}.$$

or on factoring out $\Delta x\,\Delta y\,\Delta z$ from the left hand expression.

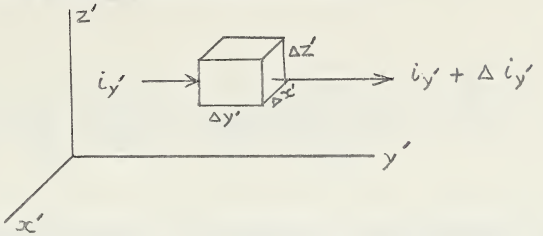
$$\left[\frac{\Delta}{\Delta x}(\rho v_x) + \frac{\Delta}{\Delta y}(\rho v_y) + \frac{\Delta}{\Delta z}(\rho v_z)\right]\Delta x.\,\Delta y.\,\Delta z. = \Delta x\,\Delta y\,\Delta z\,f\,\frac{\Delta\rho}{\Delta t}.$$

Let $\Delta x\,\Delta y\,\Delta z$ in the right hand expression be equal to V_o. resulting in the expression,

$$\left[\frac{\Delta}{\Delta x}(\rho v_x) + \frac{\Delta}{\Delta y}(\rho v_y) + \frac{\Delta}{\Delta z}(\rho v_z)\right]\Delta x\,\Delta y\,\Delta z = -V_o\,f\,\frac{\Delta\rho}{\Delta t},$$

which is the equation of continuity for fluid flow that will be used.

The equation of Continuity in Electron Flow



Consider an elemental volume, $\Delta x' \Delta y' \Delta z'$ of a conducting medium with a current, $i_{y'}$, flowing in the y direction. The current density is then $\frac{i_{y'}}{A_{y'}}$ per unit area and the total current is

$$\frac{i_{y'}}{A_{y'}} \cdot \Delta x' \cdot \Delta z' \ .$$

The current flowing out is

$$\left[\frac{i_{y'}}{A_{y'}} + \Delta \left(\frac{i_{y'}}{A_{y'}} \right) \right] \Delta x' \cdot \Delta z' \ .$$

The electron charge accumulating in the block per unit time is given by the difference between these expressions,

$$- \Delta \left(\frac{i_{y'}}{A_{y'}} \right) \Delta x' \cdot \Delta z' \ .$$

For flow in three directions, the total, accumulated charge is given by the expression,

$$- \left[\frac{\Delta}{\Delta x'} \left(\frac{i_{x'}}{A_{x'}} \right) + \frac{\Delta}{\Delta y'} \left(\frac{i_{y'}}{A_{y'}} \right) + \frac{\Delta}{\Delta z'} \left(\frac{i_{z'}}{A_{z'}} \right) \right] \Delta x' \Delta y' \Delta z' \ .$$

The accumulated electron charge per unit time is also given by the change in the product of the circuit capacity, C_E, and the voltage E,

per unit time. Therefore, those two expressions may be equated to give,

$$\left[\frac{\Delta}{\Delta x'}\left(\frac{i_{x'}}{A_{x'}}\right)+\frac{\Delta}{\Delta y'}\left(\frac{i_{y'}}{A_{y'}}\right)+\frac{\Delta}{\Delta z'}\left(\frac{i_{z'}}{A_{z'}}\right)\right]\Delta x'\Delta y'\Delta z' = -\frac{\Delta\left(C_E E\right)}{\Delta t'},$$

the equation of continuity for electron flow through a conducting medium.

APPENDIX B

Detailed Development of Unsteady State Flow Analogy

The general equations governing fluid flow through porous media and electron flow through conducting media were developed in Appendix A. The simple case of steady state flow was dealt with in the body of this dissertation. The more complex problem of unsteady state flow, and the electrical analogy required to deal with it will now be discussed.

If the density of the fluid may not be considered independent of time at a point then the right hand side of the general equation no longer equals zero.

The expression

$$V_o f \frac{\Delta \rho}{\Delta t}$$

must be altered to a similar form to the expression

$$C_E \frac{\Delta E}{\Delta t},$$

The relation between density and pressure in a single phase liquid system is given by :

$$\rho = \rho_o e^{c(P-P_o)}$$

where, ρ, is the density at a pressure, p; ρ_o, is the density at some reference pressure, P_o ; c, is the compressibility factor, and, e, is the base of the natural logarithm. Equation 1 may be differentiated to give the following equation,

$$\frac{d\rho}{dt} = c \frac{dP}{dt} \cdot \rho_o e^{c(P-P_o)} ,$$

$$\frac{d\rho}{dt} = c \rho \frac{dP}{dt} .$$

If now, a small finite block, $\Delta x \Delta y \Delta z$, be considered in the reservoir, so shaped and located, that it is possible to consider an average pressure, p, to hold throughout the block. The density, ρ, may now be considered constant, throughout the block, and therefore independent of position. The density, ρ, may now be removed as a common factor from all terms of the general equation resulting in the equation

$$\left[\frac{\Delta}{\Delta x'}\left(\frac{k_x b}{\mu}\frac{\Delta p}{\Delta x}\right)+\frac{\Delta}{\Delta y'}\left(\frac{k_y b}{\mu}\frac{\Delta p}{\Delta y}\right)+\frac{\Delta}{\Delta z'}\left(\frac{k_z b}{\mu}\frac{\Delta p}{\Delta z}\right)\right]\Delta x'\Delta y'\Delta z' = V_0 f_c \frac{\Delta p}{\Delta t}$$

while the general equation for electron flow may be rewritten in the form

$$\left[\frac{\Delta}{\Delta x'}\left(\sigma\frac{\Delta E}{\Delta x'}\right)+\frac{\Delta}{\Delta y'}\left(\sigma\frac{\Delta E}{\Delta y'}\right)+\frac{\Delta}{\Delta z'}\left(\sigma\frac{\Delta E}{\Delta z'}\right)\right]\Delta x'\Delta y'\Delta z' = c_\varepsilon \frac{\Delta E}{\Delta t'}$$

These equations are now similar in form and the following transition equations may be written.

$$\sigma = \frac{D k b}{\mu} \quad \text{or} \quad z' = \frac{D k z}{\sigma \mu},$$

$$c_E = B V_0 f_c$$

$$p = F E$$

where D, B, and F, are arbitrary scale factors.

In the case where both liquid and gas expansion must be considered, the treatment is as follows, or before, a small finite block, will be considered, so shaped and located that it is possible to consider an average pressure, p, to hold throughout the block at any time, t. The value of the density, ρ, for the fluid becomes independent of the position within the block, hence may be removed as a common factor. The right hand side of the general equation may be expressed as

$$\frac{V_o f}{\rho} \frac{\Delta \rho}{\Delta t}$$

If now it is considered that this expression is equal to two terms so that,

$$\frac{V_o f}{\rho} \cdot \frac{\Delta \rho}{\Delta t} = \left[\frac{(V_o f)_G}{\rho_G} \cdot \frac{\Delta \rho_G}{\Delta t} + \frac{(V_o f)_L}{\rho_L} \frac{\Delta \rho_L}{\Delta t} \right], \qquad (5)$$

then

$$\frac{\Delta (C_E E)}{\Delta t'} = B' \left[\frac{(V_o f)_G}{\rho_G} \frac{\Delta \rho_G}{\Delta t} + \frac{(V_o f)_L}{\rho_L} \frac{\Delta \rho_L}{\Delta t} \right]. \qquad (6)$$

Take the limits of each side of this equation to obtain

$$E \frac{d C_E}{d t'} + C_E \frac{dE}{dt'} = B' \frac{(V_o f)_G}{\rho_G} \frac{d \rho_G}{dt} + B' \frac{(V_o f)_L}{\rho_L} \frac{d \rho_L}{dt}. \qquad (7)$$

Now let

$$E \frac{d C_E}{d t'} = B' \frac{(V_o f)_G}{\rho_G} \frac{d \rho_G}{dt} \qquad (8)$$

and

$$C_E \frac{dE}{dt'} = B' \frac{(V_o f)_L}{\rho_L} \frac{d \rho_L}{dt}. \qquad (9)$$

From equation (9) by substituting the expression $C \rho_L \frac{dP}{dt}$ for $\frac{d \rho_L}{dt}$,

(See Equation 2) and letting the pressure, p, equal an arbitrary constant, F times E and the prototype time, t, equal an arbitrary constant, H, times the model time t'; it may be shown that

$$C_E = \frac{B'F}{H} (V_o f)_L C$$

Let $\frac{B'F}{H}$ equal the arbitrary constant B and as in Case I (b),

$$C_E = B (V_o f)_L C$$

Assume the gas to obey the equation of state,

$$PV = znRT$$

If the gas Volume V, is considered to be $(V_o f)_G$, then

$$P(V_o f)_G = znRT$$

Solve for n in this equation to obtain the result

$$n = \frac{P(V_o f)_G}{zRT}$$

If now n is considered to be one mole and the density, ρ, is considered to be the reciprocal of the specific volume, v_G, then

$$\frac{P}{\rho_G} = zRT$$

and

$$(V_o f)_G = n v_G$$

The expression $\frac{(V_o f)_G}{\rho_G} \frac{d\rho_G}{dt}$ then may be rewritten in the form

$$\frac{n v_G}{\frac{1}{v_G}} \cdot \frac{d\left(\frac{1}{v_G}\right)}{dt}$$

or in the form

$$n v_G^2 \frac{d\left(\frac{1}{v_G}\right)}{d v_G} \cdot \frac{d v_G}{dt}$$

which simplifies to

$$\frac{(V_o f)_G}{\rho_G} \cdot \frac{d\rho_G}{dt} = \frac{(V_o f)_G}{zRT} P \frac{d v_G}{dt} .$$

Schaeffer [5] has designed an electrical circuit to increase C_E in steps at discrete time intervals. This is accomplished by connecting a condenser already charged to the existing value of E at the moment the connection is made, thus simulating the function.

$$E \frac{\Delta C_E}{\Delta t'}$$

Now let

$$E \frac{dC_E}{dt'} = B' \frac{(V_o f)_G}{\rho_G} \frac{d\rho_G}{dt}$$

Combine this with equation (10), then the expression becomes,

$$E \frac{dC_E}{dt'} = B' \frac{(V_o f)_G}{zRT} . P . \frac{dv_G}{dt} .$$

For a short time interval, the following approximation will hold,

$$E \frac{\Delta C_E}{\Delta t'} \simeq B' \frac{(V_o f)_G}{zRT} . P . \frac{\Delta v_G}{\Delta t} . \qquad (11)$$

Now let the pressure, p, equal a constant, F, times the potential, E, and the prototype time, t, equal a constant, H, times the model time t'. Substitute these values in equation (11) to obtain the relation,

$$E \frac{\Delta C_E}{\Delta t'} = \frac{B'F}{H} \frac{(V_o f)_G}{zRT} . E . \frac{\Delta v_G}{\Delta t'}$$

If this equation is solved for ΔC_E the equation,

$$\Delta C_E = \frac{B'F}{H} \frac{(V_o f)_G}{zRT} . \Delta v_G$$

is obtained.

However, the expression, $\frac{B'F}{H}$ has already been defined equal to the arbitrary constant B, therefore the change in Capacity, ΔC_E is given by the expression

$$\Delta C_E = B \frac{(V_o f)_G}{zRT} \Delta v_G$$

This is the desired transition equation. The remaining transition equations are the same as those developed for a compressible liquid and are repeated below:

$$C_E = B\,(v_0 f)_L\,C \quad ,$$

$$\Delta C_E = B\,\frac{(v_0 f)_G}{z R T}\cdot \Delta v_G \quad ,$$

$$z' = \frac{D R z}{\sigma \mu} \quad ,$$

$$P = F E \quad .$$

Appendix C

Operating Manual for the Potentiometric Model.

This model has been constructed according to the physical principles outlined in the previous sections of this work. The general theory of the circuits themselves has been outlined in the section dealing with the design of the model, and it will be assumed that the reader is familiar with this background. This manual proposes to discuss the details of "setting up", Operating, and servicing the machine, and will deal with these topics from the viewpoint of an investigator attempting to apply the model to some problem.

I The General Description of the Model

The model is divided physically into two major sections, the pool table, and the control cabinet. The pool table contains the "well", designed to hold a contoured model representing the oil reservoir; the pantograph, and the plotting surface, designed to transfer information from the pool to a recording sheet. The control cabinet contains the electronic circuits which are divided into five units or panels, and joined by inter-panel wiring. This interpanel wiring is brought out to terminal blocks at the rear of each unit. The terminals are numbered from left to right along the terminal blocks for each unit. The terminals are referred to by the unit initial and number. The five unit initials are, P, O, C, N, and M, representing the Power unit, Oscillator unit, Null Indicator unit, Control unit, and Motor Control unit. Thus for instance a terminal referred to as, P21, would be

the twenty first terminal on the Power Supply unit. The wiring diagrams show these terminals as circles, bearing the terminal number, and appear at the right of the unit diagrams. The terminals pertaining to the unit are in the first column, while the teminals on other units to which these are connected by the interpanel wiring are shown in the second column, to enable the operator to follow this wiring. A summary of these interpanel connections is presented in Table(CI). These terminals also provide convenient checking points for servicing the model and will be reffered to again in this connection.

II The Circuit Diagrams.

The detailed circuit diagrams are presented on the forrowing pages, and will be discussed in order, starting with the lowest panel in the cabinet.

(a) The Power Supply

This unit is supplied with 110 volt A.C. mains, which enter the cabinet through a "plug in" connection located on the top of the cabinet. The unswitched mains pass through the switch, S-1, and the main 10 ampere fuses, from which they are distributed to all other parts of the model.

The first power supply provides 350 volt D.C. to the oscillator and driver stages of the oscillator unit, and 6.3 volt power to the filament circuits of these tubes. The switch operating this power supply is number four on the front of the power supply panel.

TABLE VI

Interpanel Wiring Connections From The Power Supply Panel

Terminal Number	Connected To	To Carry	Terminal Number	Connected To	To Carry
P 1	TOP	110 volt A.C.	P 13	C 2	110 volt A.C. (switched)
P 2	TOP	110 volt A.C.	P 14	N 26	150 volt D.C.
P 3	O 11	6.3 volt A.C.	P 15	N 5	150 volt D.C.
P 4	O 12	6.3 volt A.C.	P 16	N 27	90 volt D.C.
P 5	O 4	6.3 volt A.C.	P 17	N 28	70 volt D.C.
P 6	O 5	6.3 volt A.C.	P 18	N 3	70 volt D.C.
P 7	O 3	Ground	P 19	N 4	90 volt D.C.
P 8	BLANK		P 20	N 6	300 volt D.C.
P 9	O 15	400 volt D.C.	P 21	N25	300 volt D.C.
P 10	O 1	400 volt D.C.	P 22	N 29	6.3 volt A.C.
P 11	BLANK		P 23	N 30	6.3 volt A.C.
P 12	C 1	110 volt A.C. (switched)	P 24	N 1	6.3 volt A.C.
			P 25	N 2	6.3 volt A.C.

TABLE CI (Continued)

Interpanel Wiring Connections From The Oscillator Panel

Terminal Number	Connected To	To Carry	Terminal Number	Connected To	To Carry
O 1	P 10	400 volt D.C.	O 11	P 3	6.3 volt A.C.
O 2	BLANK		O 12	P 4	6.3 volt A.C.
O 3	P 7	Ground	O 13	P 7	Ground
O 4	P 5	6.3 volt A.C.	O 14	BLANK	
O 5	P 6	6.3 volt A.C.	O 15	P 9	400 volt D.C.
O 6	C 3	Pool 400 cycle	O 16	BLANK	
O 7	C 4	Pool 400 cycle	O 17	N 11	Phase Det. 400 cycle (pool)
O 8	C 5	Pot. 400 cycle (C.T.)	O 18	N 12	Phase Det. 400 cycle (pool)
O 9	C 6	Pot. 400 cycle	O 19	N 19	Phase Det. 400 cycle (pot.)
O 10	C 8	Pot. 400 cycle	O 20	N 20	Phase Det. 400 cycle (pot.)

Interpanel Wiring Connections From The Control Panel

Terminal Number	Connected To	To Carry	Terminal Number	Connected To	To Carry
C 1	P 12	110 volt A.C. (switched)	C 13	N 18	Pot. Bal. Meter
C 2	P 13	110 volt A.C. (switched)	C 14	N 13	Pool Bal. Meter
C 3	O 6	Pool 400 cycle	C 15	P 23	6.3 V.A.C. (relay)
C 4	O 7	Pool 400 cycle	C 16	N 14	Pool Bal. Meter
C 5	O 8	Pot. 400 cycle(C.T.)	C 17	N 23	110 V.A.C. (relay)
C 6	O 9	Pot. 400 cycle	C 18	N 24	110 V.A.C. (relay)
C 7	O 3	Ground	C 19	BLANK	
C 8	O 10	Pot. 400 cycle	C 20	M 3	Pool Motor Control
C 9	N 8	110 V. A.C. (relay)	C 21	M 5	110 V.A.C. Pool Motor
C 10	N 15	Voltmeter 400 cycle	C 22	M 5	110 V.A.C. Pool Motor
C 11	N 16	Voltmeter 400 cycle	C 23	M 15	Pot. Motor Control
C 12	N 17	Pot. Bal. Meter	C 24	M 16	110 V.A.C. Pot. Motor
			C 25	M 18	110 V.A.C. Pot. Motor.

TABLE CI (Continued)

Interpanel Wiring Connections From The Null Indicator Panel

Terminal Number	Connected To	To Carry	Terminal Number	Connected To	To Carry
N 1	P 24	6.3 volt A.C.	N 16	C 11	Voltmeter 400 cycle
N 2	P 25	6.3 volt A.C.	N 17	C 12	Pot. Bal. Meter
N 3	P 18	70 volt D.C.	N18	C 13	Pot. Bal. Meter
N 4	P 19	90 volt D.C.	N 19	O 19	Phase Det. 400 cycle (pot.)
N 5	P 15	150 volt D.C.	N 20	O 20	Phase Det. 400 cycle (pot.)
N 6	P 20	300 volt D.C.	N 21	M 11	Pot. Motor Control
N 7	P 7	Ground	N 22	M 12	Pot. Motor Control
N 8	C 9	110 V.A.C.(relay)	N23	C 17	110 V.A.C. (relay)
N 9	M 9	Pool Motor Control	N 24	C 18	110 V.A.C. (relay)
N 10	M 10	Pool Motor Control	N 25	P 21	300 volt D.C.
N 11	O 17	Phase Det. 400 cycle (pool)	N 26	P 14	150 volt D.C.
N 12	O 18	Phase Det. 400 cycle (pool)	N 27	P 16	90 volt D.C.
N 13	C 14	Pool Bal. Meter	N 28	P 17	70 volt D.C.
N 14	C 16	Pool Bal. Meter	N 29	P 22	6.3 volt A.C.
N 15	C 10	Voltmeter 400 cycle	N 30	P 23	6.3 volt A.C.

TABLE CI (Continued)

Interpanel Wiring Connections From The Motor Control Panel

Terminal Number	Connected To	To Carry	Terminal Number	Connected To	To Carry
M 1	BLANK		M 11	N 21	Pot. Motor Control (D.C.)
M 2	BLANK		M 12	N 22	Pot. Motor Control (D.C.)
M 3	C 20	Pool Motor Control (A.C.)	M 13	N 25	300 volt D.C.
M 4	BLANK		M 14	N 7	Ground
M 5	C 21	Pool Motor 110 V.A.C.	M 15	C 23	Pot. Motor 110 V.A.C.
M 6	C 22	Pool Motor 110 V.A.C.	M 16	C 24	Pot. Motor 110 V.A.C.
M 7	N 7	Ground	M 17	BLANK	
M 8	N 6	300 volt D.C.	M 18	C 25	Pot. Motor Control (A.C.)
M 9	N 9	Pool Motor Control (D.C.)	M 19	P 12	110 volt A.C. (switched)
M 10	N 10	Pool motor Control (D.C.)	M 20	P 13	110 volt A.C. (switched)

The second power supply provides 350 volts D.C. to the two "push-pull" output stages. It will be noted that the negative return of this supply is through the centre tap of the filament winding of the transformer, through the current jack, J-1, mounted on the front of the panel, and through the decoupled 160 ohm bias resistor. The jack, J-1, is shunted to give a multiplying ratio of one hundred. Thus the current of approximately 160 milliamperes is read as 1.6 milliamperes on the current meter, when this meter is plugged into the jack. The 160 ohm bias resistor has an adjustable tap which may be altered to change the bias if necessary. This resistor is located underneath the chassis of the power supply unit.

The third Power Supply provides D.C. voltages of 250, 150, 90, and 70 volts to the pool balance Null Indicator, together with 6.3 volt A.C. to the filaments of these tubes. The 150 volts is stabilized by the voltage regulator tube and this stabilization also opperates on the 90, and 70 volt supplies. The switch for this power supply is located on the front of the panel together with its fuse, and is switch number three on the panel.

The fourth power supply is similar to the one just described, and provides power to the Potentiometer Null Indicator. The switch controling this power supply is number two on the front panel.

(b) The Oscillator Unit

It was suggested earlier that this unit required some modification, that a seperate gain control for the potentiometer was required. It is suggested that an extra triode tube be added to supply this requirement, in parallel with the present 6V6 drivers. The variable frequency controls should be ganged together, leaving space for the extra gain control in the grid circuit of the new tube. The present controls are all labeled on the front panel together with the current jacks for the two oscillator tubes, the preamplifier tube, and the two driver tubes.

(c) The Control Unit

The control unit contains the bulk of the controls needed during the operation of the model. The front panel is divided into three banks or sections. The left hand bank contains thirty variable current control resistors, arranged in six horizontal rows of five controls each. The top four rows contain the output current controls and are numbered from left to right along the rows from one to twenty. The lower two rows contain the input current controls and are numbered from one to ten.

The second bank of controls contains the potentiometer indicating dials, the potentiometer range change switch, and the model "function" switch. This five position gang switch controls the action of the model and specifically connects the potentiometer in the correct polarity to each of the measurement stations as required.

The third bank of controls contains the current selector switches, the potentiometer phase control, and the reference earth control. The current selector switches are eleven position rotary switches. The top switch is the first output selector, and its positions are numbered from one to ten, with the eleventh position marked 11-20. When the first switch is in this position, the second switch comes into use, and the positions of this switch are numbered from eleven to twenty, and "off". The third switch is also an eleven position rotary switch, and is used to select the input currents to be measured.

The next control in the third bank is the potentiometer phase control. This control is provided with a large vernier dial for ease in making fine adjustments, and although not marked is easily identified. Beside the phase control, is mounted the potentiometer reference earth control used when plotting isopotential lines. Below the reference earth control is a toggle switch, mounted on the connector panel. This is the balance motor change over switch, also used during the plotting of isopotential lines, and it is this switch which allows the search array to seek an isopotential line rather than a current line in the pool.

(d) The Null Indicator Unit

This unit contains two null indicators, the pool balance and the potentiometer balance indicators. The two circuits are laid out and wired in such a fashion that one circuit forms a mirror image of the other with the centre line of the unit as the mirror plane. Some of the controls of this unit are in the form of screwdriver presets and are located at the rear of the chassis. It is most convenient to discuss these controls from the centre outwards alond the row. The two nearest the centre are the cathode trimmer condencers of the diffirential detector circuits. The third control from centre is the input balance control of the differential detector. The fourth control in the case of the potentiometer null indicator, is the phase shifter, while the fifth control is the frequency control. In the case of the pool null indicator, both of these controls are in the frequency sensitive network, and if it is desired to add a phase shifter to this circuit, one of these controls could be used.

The controls mounted on the front of the panel are also arranged symmetrically, about the centre line, and will once more be discussed from the centre out. The first control is the grid shorting push button used whenever the plate circuit of the D.C. amplifier is being adjusted to balance. This push button connects the two grids together, ensuring that they are at the same potential. The second control is the plate balance control of the D.C. amplifer. The third control adjusts the grid bias of the phase detector to balance this circuit and is referred to as the grid balance

control. The final control on this panel is the null indicator amplifier gain control, and is referred to as the "null gain" control.

The null indicator unit also contains the indicating instruments used in conjunction with the model. The meter on the left hand side is called the current meter. This meter is connected to the jack mounted directly below it on the panel and may be inserted in any of the cathode circuits of the set by using the plug cord provided. In use, one end of this cord is plugged in to the meter jack, and the other end is then plugged in to any one of the current jacks provided, on the front of the cabinet. The central meter is the high frequency voltmeter provided for the standardization of the voltage applied to the potentiometer circuit. The third meter is a monitoring instrument, by which the operator may check the performance of either null indicator. A three position switch is provided below the meter by which the meter may be connected into either circuit or left disconnected when not in use.

(e) The Motor Control Unit

This unit is supplied with mains voltage, through the main switch of the power supply unit, and also draws D.C. power from the null indicator units. The A.C. mains pass through switches on the motor control unit, so that the motors may be shut off while the remainder of the circuits are being adjusted. The motor control unit is so designed that no damage will result if either of the two supplies are

connected while the other is not. The motors of course will not rotate unless both the A.C. and D.C. sourses are connected. The motor control unit has one variable control, which adjusts the bias of the control tubes. This control acts as a balance control for the motor and is set so that the motor stops rotating when the null meter indicates balance.

II Preparing The Model For Operation

The first essential step in the application of this model to an oil reservoir problem, is the accumulation of all the available pertinent data concerning the field to be studied. When this has been done, the data must be converted into a form which the model can use. In this connection, a scale map of such a size, that all of the area of interest will fit within the space of the pool, must be constructed. This map should show the locations of all wells, and should show the contours of the variations in the permeability-depth product throughout the field. A transparent overlay map showing the variations in porosity should also be prepared using the same scale. A list of the flow rates of each well is also required.

The next step is the construction of the contoured basin. The outer container could be made from "jig wood," or some other non conductor, in the shape of a shallow box. The contour map must be transferred to the bottom of this box. It is suggested that the pantograph, with a stylus substituted for the four probe array, might be useful in this regard. Laminated sheets whose thickness is proportional to the contour interval, could then be cut to the shape of the contour lines, and these sheets stacked in position. The well locations would then be marked out and holes drilled through the stacks for the insertion of the electrodes. The inside of the basin should then be given a heavy coat of parafin wax to make it waterproof.

(a) Adjusting The Oscillator.

There are few adjustments required for the operation of this unit. With the model switched on and an oscilloscope connected to one of the oscillator output terminals, check the waveform for shape. A true sine wave is required for correct operation, and the controls may be set too near maximum with the result that the output stages are overloaded and distort the waveform. The phase reference voltage should be increased until the current in jack, J-8, reads Between 0.5 and 1.0 milliamps.

(b) Adjusting The Null Indicator

With the set switched on and the oscillator adjusted as above, depress the grid shorting push button, and check for balance with the balance meter. If the meter does not indicate balance, adjust the plate balance control until null is obtained. Next, with the null gain control set to zero, check for balance with the balance meter. If balance is not obtained, adjust the grid balance control until balance is restored.

To balance the input circuit, it is most convenient to use an oscilloscope connected between the grid of the phase dectector tube and ground. The null gain control should be set at maximum for this reading. It is convenient to remove the Phase detector tube from its socket and insert the oscilloscope probe into the grid socket. The two grids of the differential detector must be shorted together and connected to a common sourse of 400 cycle power in order to check for balance.

To supply the test signal for the null input balance just described, a special connector lead has been provided. This lead replaces the one normally connecting the pool indicator to the isopotential probes, and is connected between the connector panel and the table. This lead serves the double purpose of shorting the two grids together and at the same time applying a common mode signal between the grids and ground. To balance the potentiometer null indicator input, this same signal can be applied to the input stage by plugging the pool input leads into the potentiometer input sockets on the top of the null indicator chassis.

When this common mode signal has been connected, the input balance control should be adjusted until minimum signal is shown on the oscilloscope. The trimmer condensers are then adjusted if any further adjustment is needed. Replace the phase detector tube and check that the circuit is still at balance as shown on the balance meter. If balance is not established, then the phase adjustment requires resetting.

(c) Phase Adjustments On The Model

There are two sets of signals whose phase relationship must be correct before the null indicators will function properly. The input signals to the differential detectors must be in phase, if the detector is to function. In the case of the pool indicator this phasing is automatic and requires no adjustment. However, the potentiometer null indicator receives its signals from two different sourses and it is necessary to correct the phase relation between the two.

To accomplish this phase adjustment, proceed as follows. With the set switched on and connected for normal operation, switch the function switch to the input isopotential position, and rotate the potentiometer range change switch fully counterclockwise. This will provide a large input signal to both grids of the input differential detector. Now, remove the mixer tube, 12AX7, from its socket, and connect the oscilloscope between ground and,the grid of this tube socket. Connect the vertical deflection amplifier of the oscilloscope between cathode and ground, to obtain the lissajous figure showing the phase relationship between the two voltages. It may be necessary to adjust the reference earth control, to obtain two signals of approximately the same amplitude. The potentiometer phase control is now adjusted until the two signals are in phase. Replace the mixer tube. The differential detector should now pass the true error signal, Δe.

The second phase adjustment required, concerns the relation between the error signal, and the phase reference signal. To check this relationship, remove the phase detector tube and connect the horizontal sweep of the oscilloscope to the grid of this tube. Connect the vertical sweep to one of the rear terminals carrying the phase reference signal, and obtain the lissajous figure depicting the phase relation between the two signals. Now adjust the null indicator phase control until the two signals are in phase. In the case of the pool null indicator, it was found that a 0.5 mfd. condenser in parallel with the pool supply electrodes was sufficient to correct this phase relation and no control was provided. However this might not be the case when

a large and complex model is being examined, hence the reccomendation that this control be added.

The model should now be ready for automatic operation. Before switching on the balance motors however, first rotate the four probe array, with the function switch in the gradient position. The balance meter should now respond readily and indicate a sharp null point. It is now permissable to switch on the pool motor and allow the four probe array to balance automatically. In regions of high gradient it may be necessary to turn down the null gain control to prevent cycling. The potentiometer shaft should also be rotated by hand to prove that balance exists before switching on the balance motor.

(d) Adjusting the Motor Control Unit

When the above adjustments have been made and it is possible to switch on the motors, The waveform of the control voltage to the motor should be checked. Connect the oscilloscope to the motor control terminal (M 3, and M 18) and allow the motor to come to balance. The bias control is now adjusted until minimum signal is obtained. It has been found that this setting is not critical and requires very little attention.

III Servicing The Model

Any piece of electronic equipment requires attention if it is to function properly. Most breakdowns can be prevented if the machine is regularily ckecked over. The most obvious service requirement is that of cleanliness. Dust tends to accumulate on high voltage wiring and should be regularily removed. A small paint brush is recommended for this purpose. Switch contacts exposed to the atmosphere should also be cleaned from time to time. A camel's hair brush dipped in carbon tetrachloride makes a good cleaning agent. While the operator is cleaning the set the components should be examined for external signs of deterioration. A resistor showing signs of overheating should be replaced before a burnout occurs.

The pool unit also requires periodic cleaning, as the room is quite dusty and this dust collects in the electrolyte. Experience has shown that the pool should be drained at least once a week, the pool washed out and the electrodes cleaned. Although corrosion of these electrodes is not a major problem, some does occur especially near the surface of the electrolyte, where the dust also seems to collect. The copper search probes should also be cleaned, they do not appear to corrode but do collect dust as they are in contact with the surface of the liquid. It was also found necessary to filter the electrolyte to remove foreign bodies. This was done by forcing the electrolyte out of the storage vessel, with compressed air, through a filter and back into the cleaned tank.

If an attempt is made to calculate actual prototype transit times, it is necessary to keep the electrolyte conductivity constant and also know the value of this property. Thus it will be necessary to construct a conductivity cell which may be placed in the pool and connected between two of the pool supply terminals. The current through the cell may be measured by the potentiometer in the normal manner. It will be necessary to supply a pair of temporary leads from the master voltmeter to the cell, to obtain the applied voltage. The cell should be initially calibrated against a standard solution.

The probe spacing and orientation should also be checked periodically. To check the spacing, press a sheet of paper against the tips of the probes, then check that the diagonals so formed, are of equal length and form a right angle. Also check that this spacing is the same on the plotting array. The orientation is most easily checked by first establishing the location of one line in the pool as previously described and making sure that the plotting array reproduces this line.

Thermionic tubes deteriorate with time and the tubes in service in this model should be regularily checked. For this purpose, current jacks have been built into the set and if regular current readings are taken it is possible to detect and replace failing tubes before they cause trouble, and in any event rapidly locate any trouble that does occur. A set of current readings is presented in Table IIC, and while these are typical readings it should be understood that some of them are sensitive to changes in control settings, and a master set should be made

TABLE IIC

Typical Meter Readings For The Potentiometric Model

Jack Number	Meter Reading (milliamperes)	Multiplying Factor
J 1	1.5	100
J 2	2.7	20
J 3	1.2	10
J 4	1.0	1
J 5	1.2	1
J 6	2.7	20
J 7	1.0	10
J 8	0.7	1
J 9	0.4	1
J 10	0.7	1
J 11	0.5	1
J 12	0.6	1
J 13	0.5	1
J 14	0.5	1
J 15	0.4	1
J 16	0.8	1
J 17	0.4	1
J 18	1.2	10
J 19	0.6	10
J 20	0.6	10

whenever the model is first set up and operating. Future readings could then be compared with this set and any changes should be investigated. When it is necessary to trace a fault in the equipment it will be found that most faults will produce a radical change in one or more of the meter readings, and when this is observed the faulty circuit has been located. The time spent in locating a fault is thus greatly reduced.

Periodic voltage readings should also be made on the output terminals of the power supply panel. These readings should agree with the values given in Table Ic. Any large changes in these readings should be investigated, especially any large decrease in one of the D.C. lines, as such a decrease might be caused by a breakdown of one of the electrolytic smoothing condensers, which are operating very near their rated limits. In this regard it should be noted that these power supplies should never be switched on unless they are connected to a load, as with no load, the smoothing condensers will charge to the full peak voltage and will fail.

IV Tracing Faults On The Model.

It has been pointed out earlier in this discussion, that the model has certain features built in, which facilitate the location of faults when they occur. The balance and current meters will very often be useful in locating the trouble. Two auxillary test instruments are required for servicing the model, and these are a universal vacuum tube voltmeter and an oscilloscope. It is recommended that the operator become familiar with the operation of these instruments, as some skill in their use is required when operating the model.

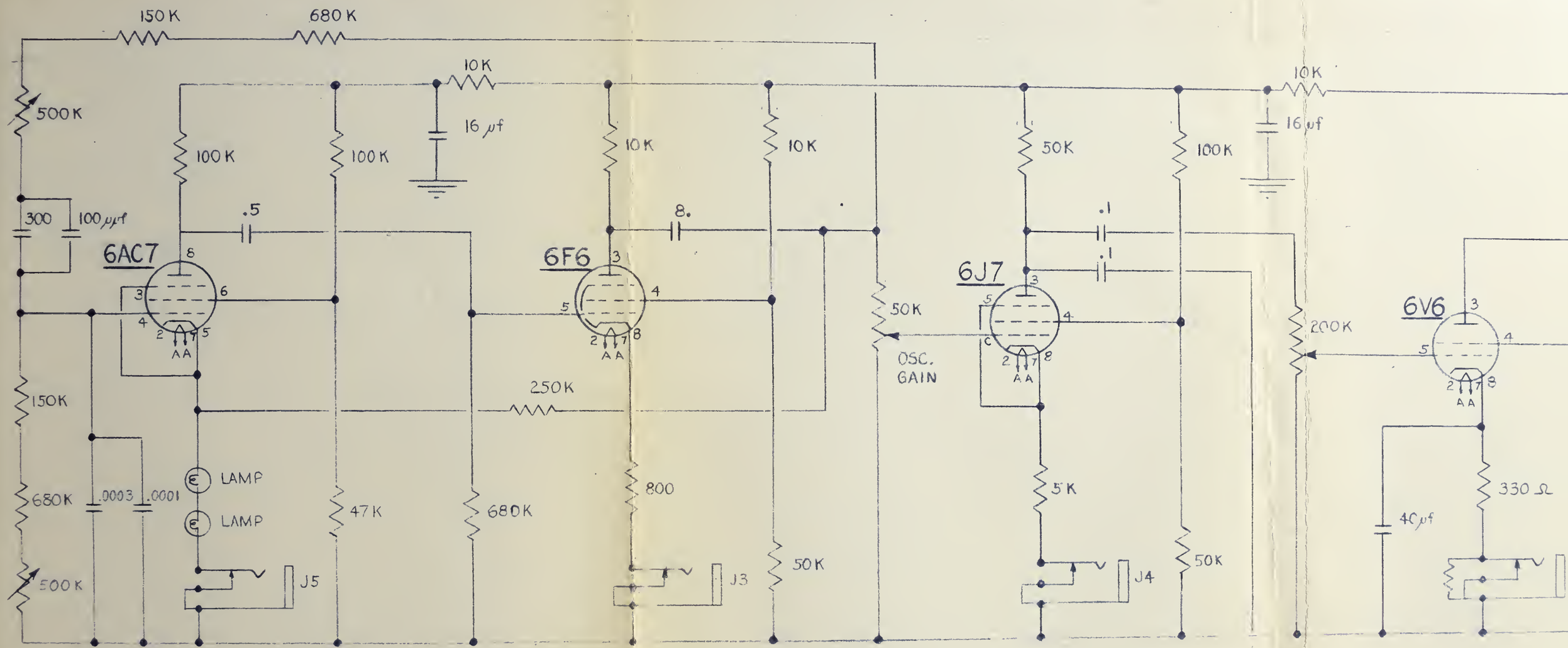
Any failures in the power supply circuits should be immediatly located from a check of the current and voltage readings. a check of the components of the faulty circuit should reveal the fault with little trouble.

A failure in the oscillator unit will in most cases be detected by the current readings. If however these appear normal, it is necessary to start at the oscillator and follow the signal from stage to stage, until the point is reached where the trouble is. This tracing of the signal through the set is done by means of the oscilloscope. When the fault has been traced to a single stage, it is usually most convenient to remove the unit from the set and check the component values with the universal tester. This method should locate all but the most stubborn faults.

The same general comments apply to the location of faults in the null indicator and motor control circuits. This general tracing procedure, combined with a knowledge

of what should be occurring in each circuit, will enable the operator to locate and repair all faults which may occur.

If then, the model ceases to function for any reason the following is the general procedure to be followed. First, make an immediate check of all current and voltage readings. If this does not definitely isolate the fault, proceed with the general setting up procedure, until some abnormality becomes apparent. This abnormality will indicate which unit is at fault. Proceed to trace the desired signal through this unit from input to output until the faulty stage is located. The nature of the fault will usually point to some component in the stage as being the point of failure, however in case of doubt ckeck the performance of all the components associated with the stage until the failure is discovered.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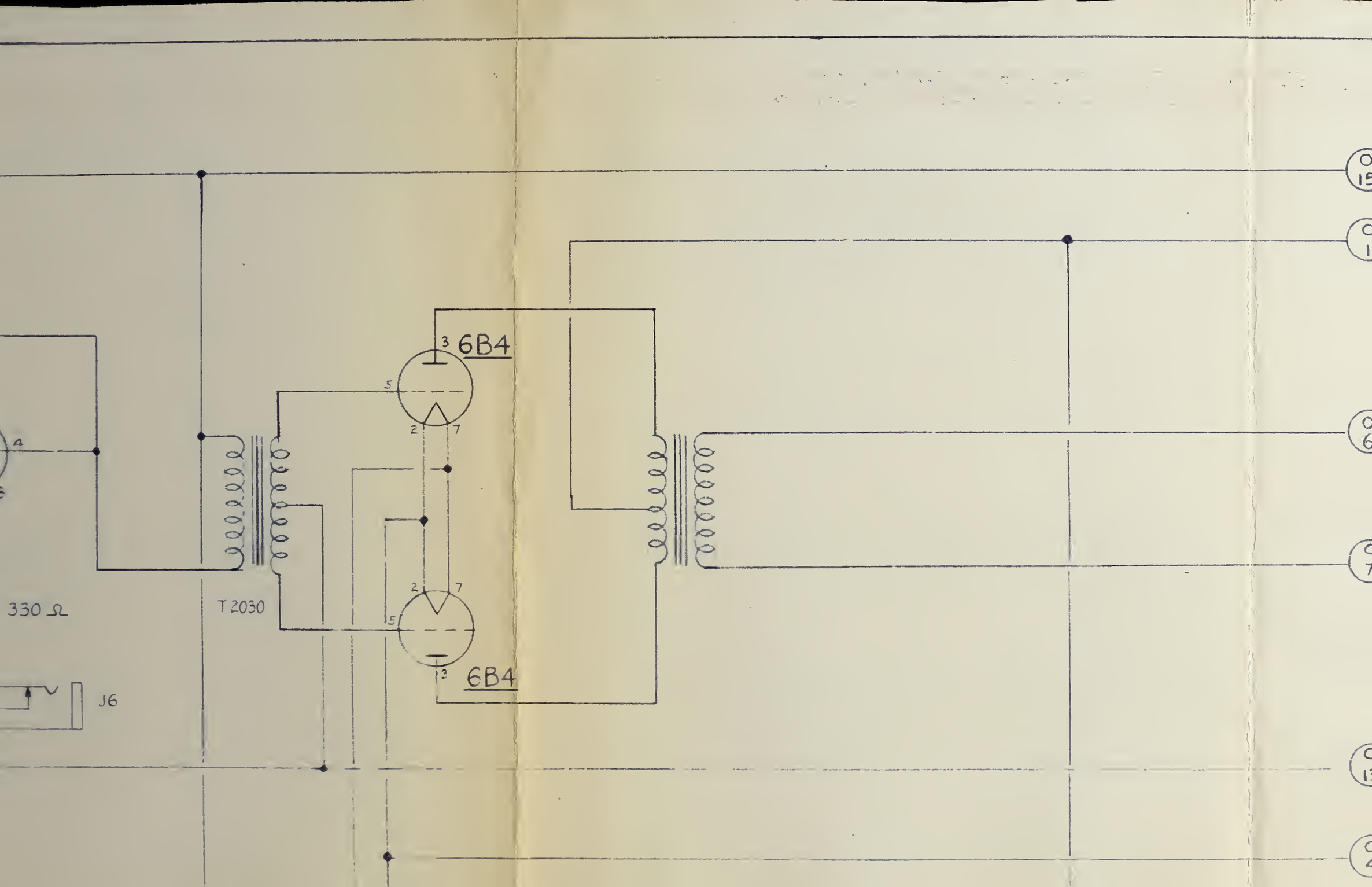
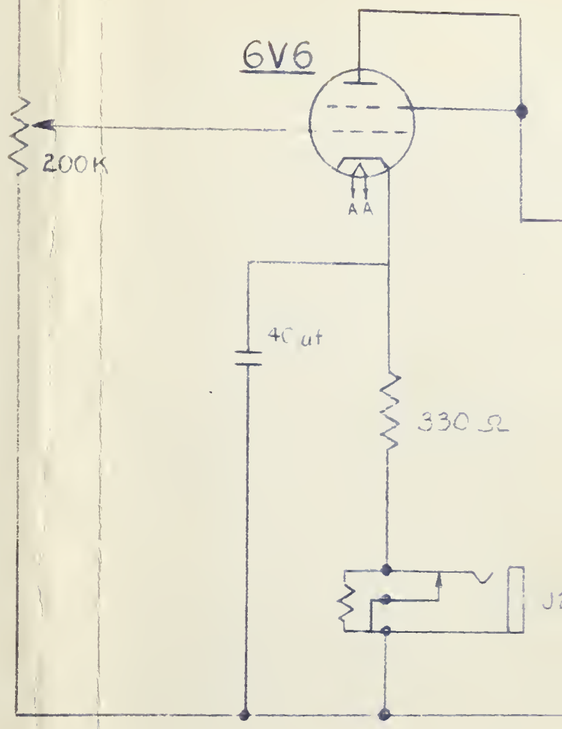
680 K
10 K
500 K
100 K
100 K
16 μf
10 K
10 K
50 K
100 K
10 K
16 μf
300
100 μμf
.5
8.
.1
.1
6AC7
6F6
6J7
6V6
50 K
OSC.
GAIN
200 K
250 K
150 K
680 K
.0003
.0001
LAMP
LAMP
47 K
680 K
800
5 K
50 K
50 K
40 μf
330 Ω
500 K
J5
J3
J4


3 6B4
5
2
7
T 2030
330 Ω
J6
2
7
5
13
6B4



UNIVERSITY OF ALBERTA

DEPARTMENT OF CHEMICAL
AND PETROLEUM ENGINEERING

POTENTIOMETRIC MODEL

CIRCUIT DIAGRAM OF OSCILLATOR PANEL

DRWN: W.K.S

DATE: 13 MAY '52

6B4

T 2030

6B4

J2

O 17 — N 11

O 18 — N 12

O 9 — C 6

O 8 — C 5

O 10 — C 8

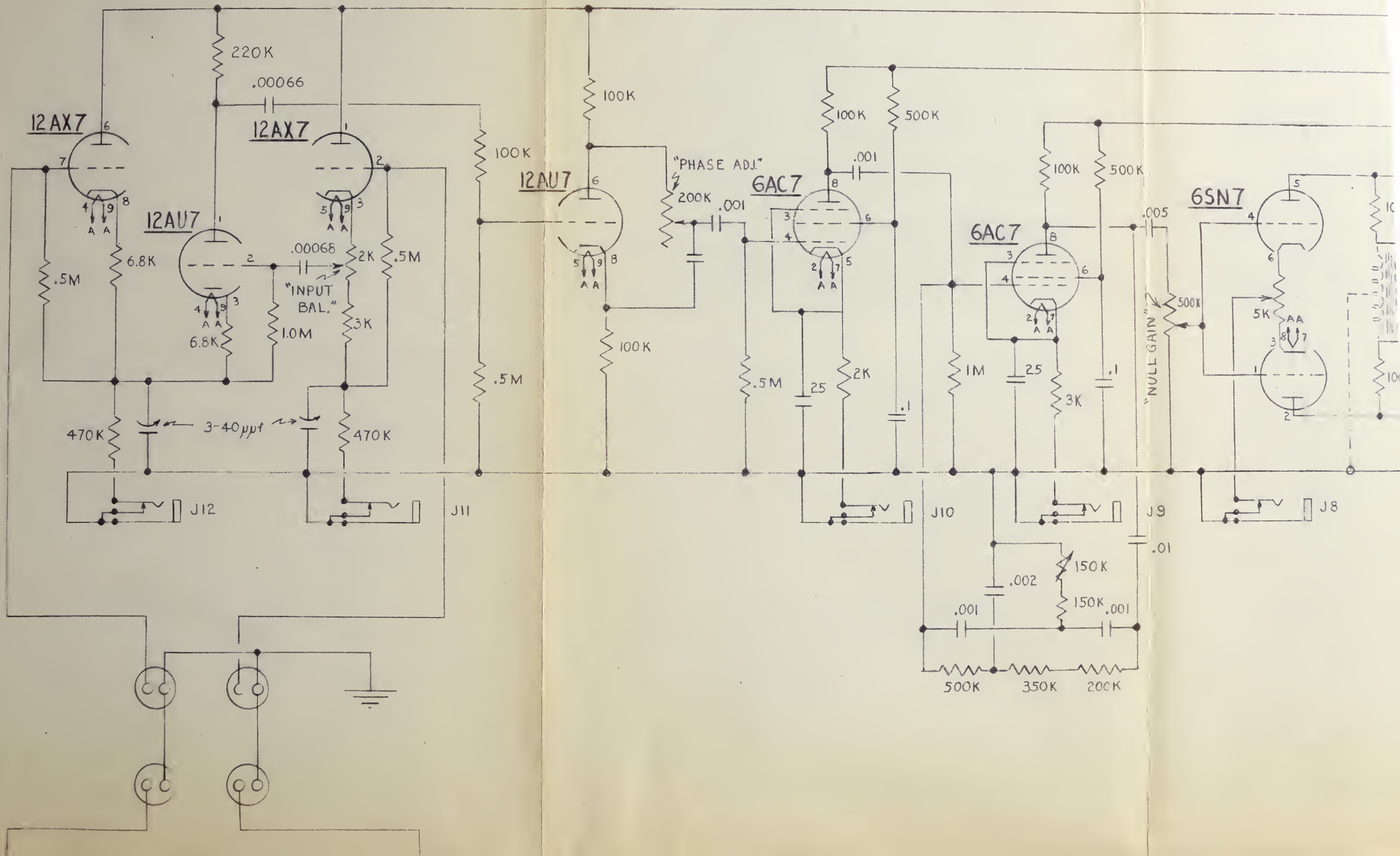
O 19 — N 19

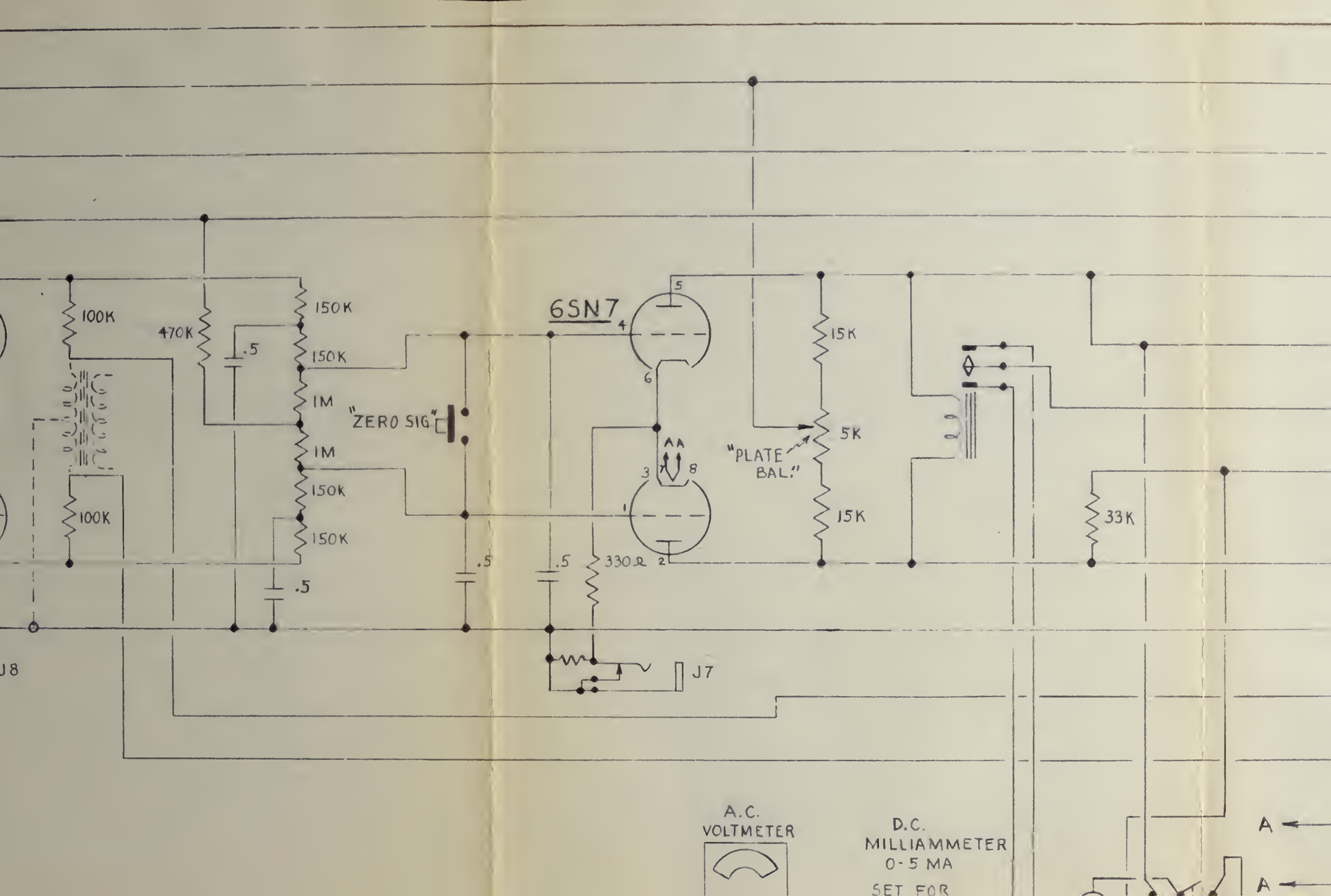
O 20 — N 20

O 13 — P 7

A ← O 11 — P 3

A ← O 12 — P 4


12AX7
12AX7
12AU7
12AU7
6AC7
6AC7
6SN7
220K
.00066
100K
6.8K
.5M
.00068
2K
.5M
"INPUT BAL."
1.0M
3K
6.8K
470K
3-40 μμf
470K
.5M
100K
"PHASE ADJ."
200K
.001
100K
100K
500K
.001
.5M
25
2K
.1
100K
500K
1M
25
3K
.1
.005
"NULL GAIN"
500K
5K
.01
150K
.002
150K
.001
.001
500K
350K
200K
J12
J11
J10
J9
J8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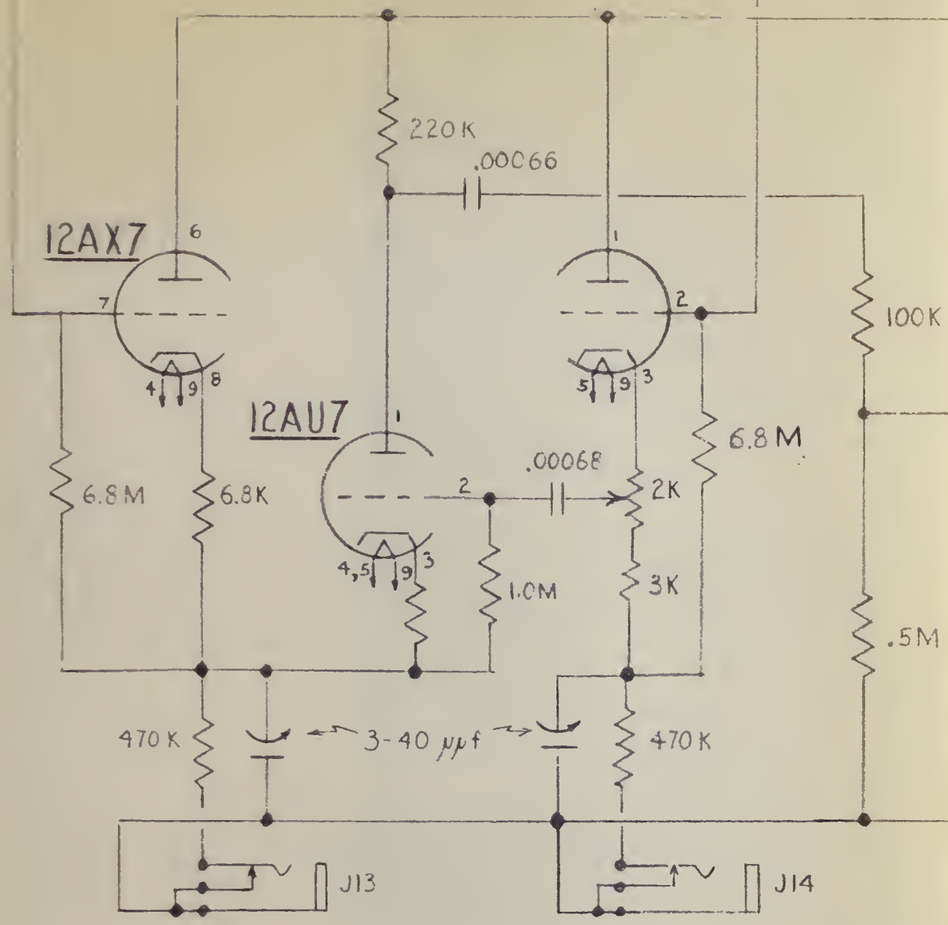
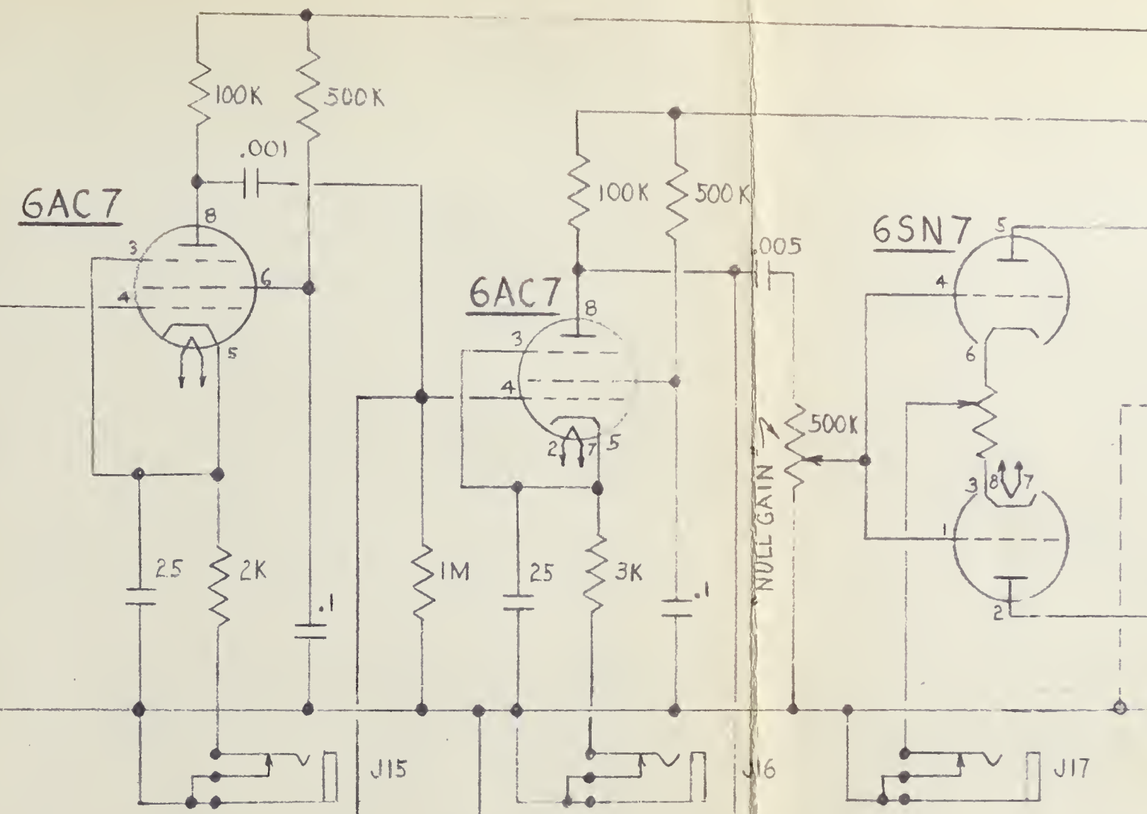
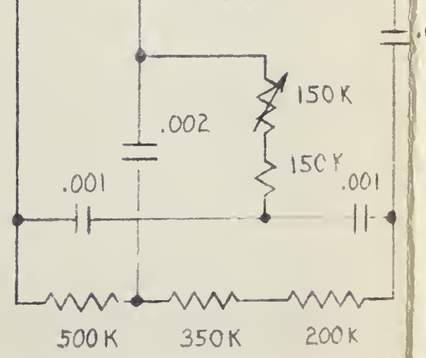
150K
150K
1M
"ZERO SIG"
1M
150K
150K
100K
.5
J8
6SN7
5
4
6
3
8
1
2
.5
.5
330Ω
J7
15K
5K
"PLATE BAL."
15K
33K
A.C.
VOLTMETER
D.C.
MILLIAMMETER
0-5 MA
SET FOR
A
A







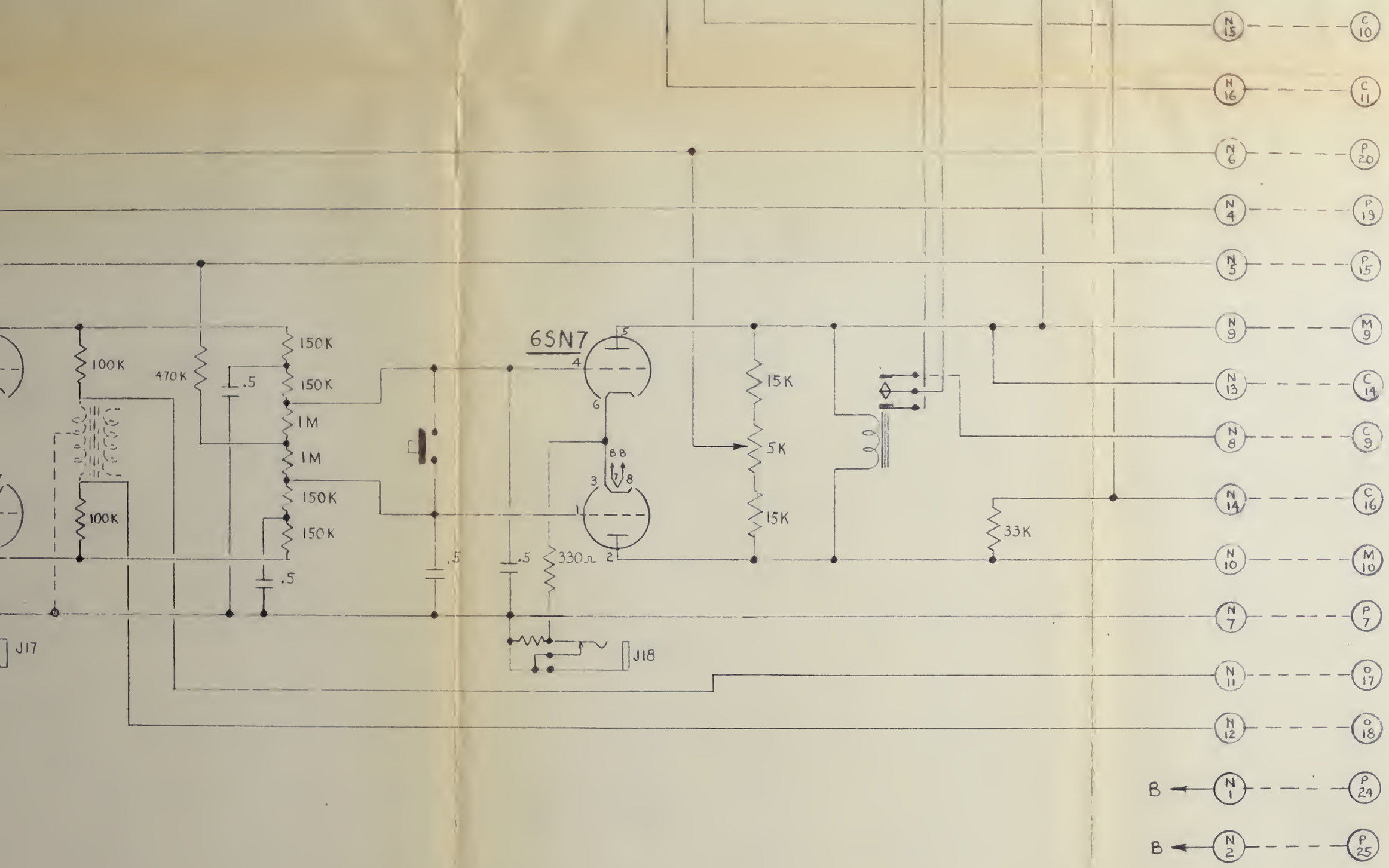
UNIVERSITY OF ALBERTA
DEPARTMENT OF CHEMICAL
AND PETROLEUM ENGINEERING

POTENTIOMETRIC MODEL

CIRCUIT DIAGRAM OF NULL INDICATOR PANEL

SCALE NONE DRWN:

CHKD: DATE: 22 MAR 52


6SN7
100K
470K
.5
150K
150K
1M
1M
150K
150K
100K
.5
.5
.5
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5K
15K
33K
J17
J18
N 15
C 10
N 16
C 11
N 6
P 20
N 4
P 19
N 5
P 15
N 9
M 9
N 13
C 14
N 8
C 9
N 14
C 16
N 10
M 10
N 7
P 7
N 11
O 17
N 12
O 18
B
N 1
P 24
B
N 2
P 25

100 Ω

500 Ω

POOL BAL.
MOTOR

G

OUTPUT CURRENT
SELECTOR

"INPUT ISOPOTENTIAL"

"OUTPUT ISO"

"GRADIENT"

"INPUT MA"

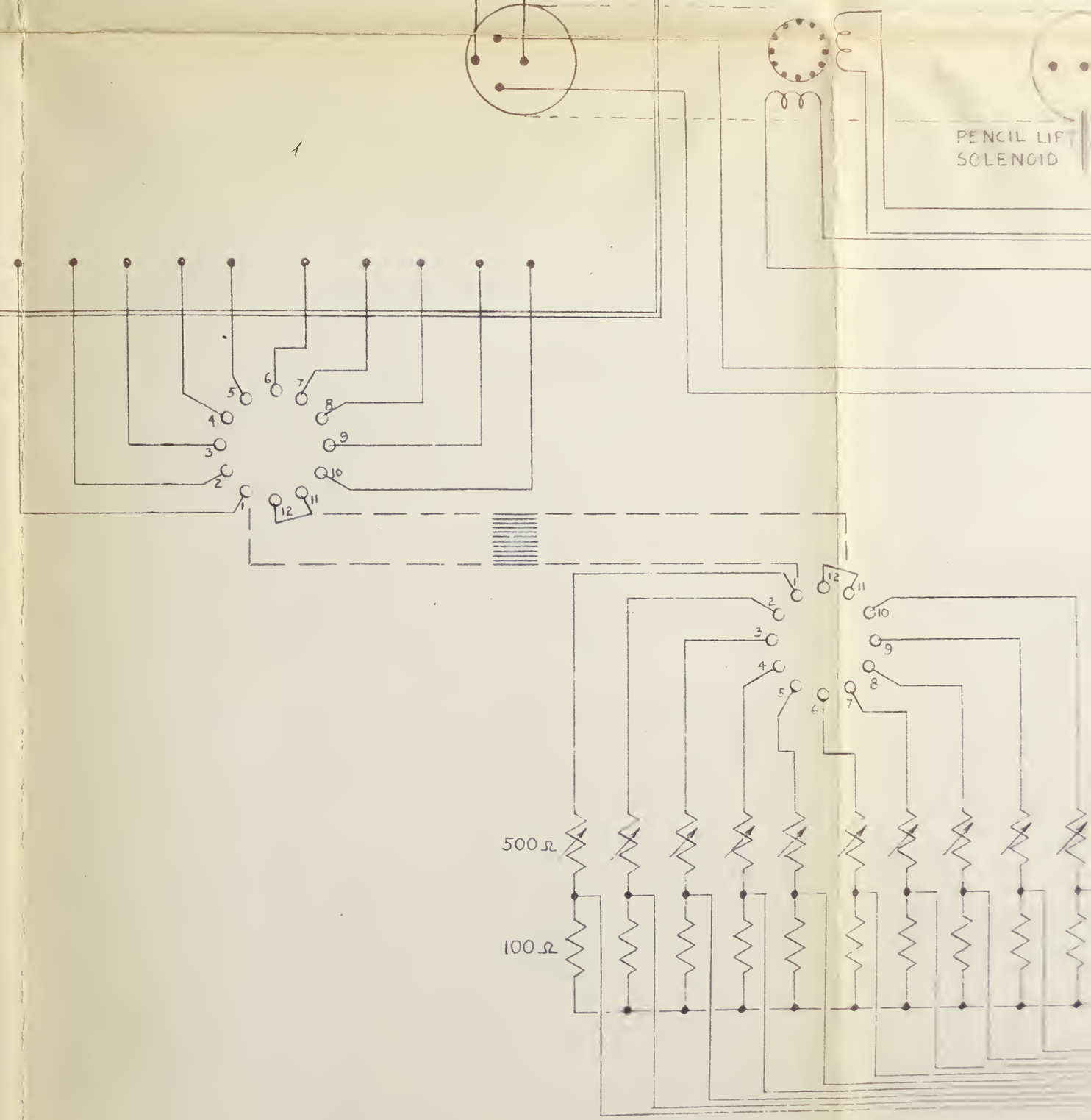
"OUTPUT MA"

PENCIL LIFT
CHANG OVER RELAY

MOTOR CHANGE OVER
RELAY

C 12 — N 17
C 13 — N 18
C 14 — N 13
C 16 — N 14
C 3 — O 6
C 5 — O 8
C 9 — N 8
C 17 — N 23
C 18 — N 24
C 20 — M 3
C 23 — M 15
C 1 — P 12
C 2 — P 13

POOL



UNIVERSITY OF ALBERTA

DEPARTMENT OF CHEMICAL AND PETROLEUM ENGINEERING

POTENTIOMETRIC MODEL

CIRCUIT DIAGRAM OF POTENTIOMETER & CONTROL UNIT

SCALE: NONE DRWN: W.L.

CHKD: DATE: 23 MAR '52

TO POOL
N.I.

TO POT.
N.I.

MOTOR
REVERSE RELAY

POT. BAL.
MOTOR

.0002 .002
10-50

.0002 .002
10-50

.002

50K

C 6 — O 9

C 8 — O 10

RANGE
SW.

40 40
10-50 10 50

.001 .0005 .0003 10 50

.01 .0075 .01 .0075
10-50 10-50

C 10 — N 15

C 11 — N 16

C 7 — P 7

250K

POOL
REFERENCE
EARTH

POT.
MOTOR
REVERSE SW.

20-1100 μμf
LINEAR

10-75 μμf
TYPE-SE-75

C 4 — O 7

C 15 — P 23

INPUT CURRENT
SELECTOR

OFF

C 21 — M 5

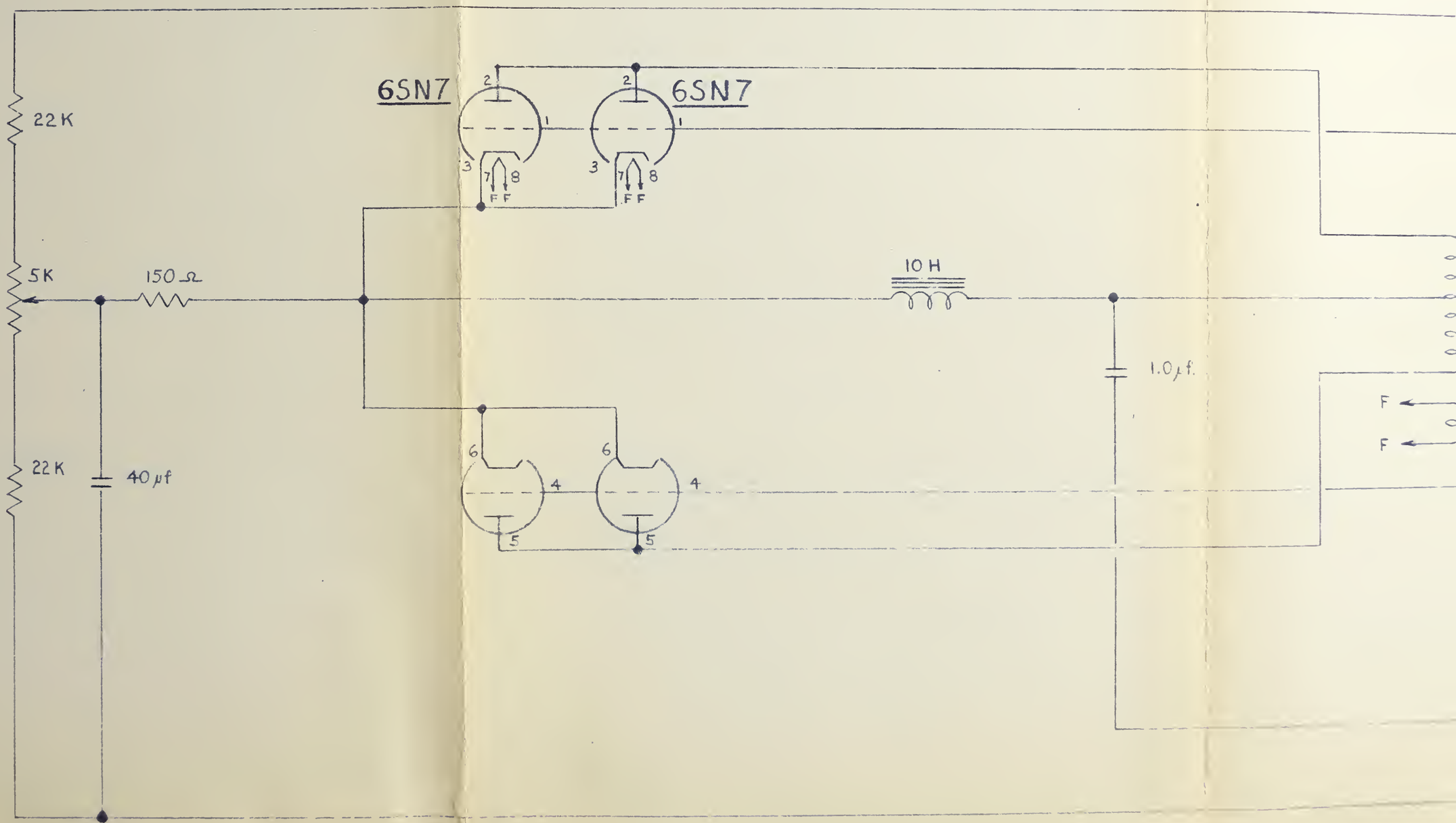
C 22 — M 6

C 24 — M 16

C 25 — M 18

C 2 — P 13

P 1 — 12


6SN7
6SN7
22K
5K
150Ω
22K
40μf
10 H
1.0μf.
F
F

F

F

1.0 μf

M 8 — P 20

M 9 — N 9

M 10 — N 10

M 19 — P 12

M 20 — P 13

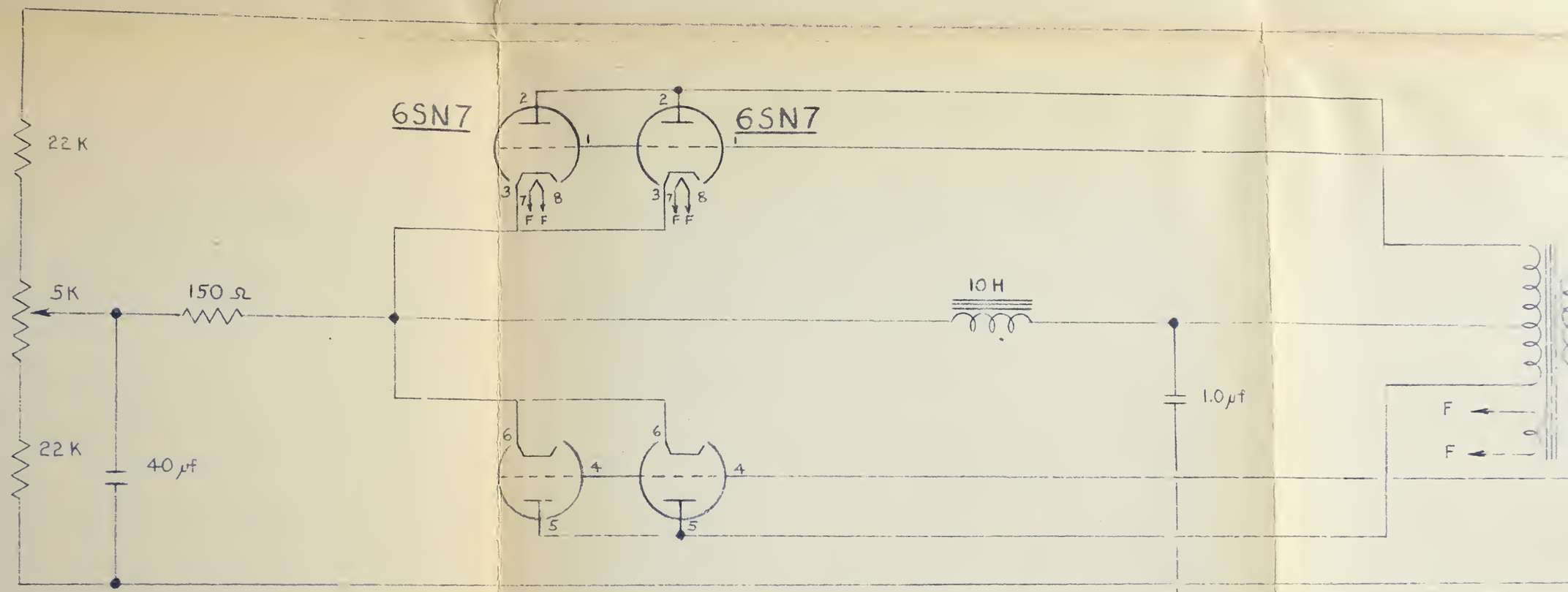
M 5 — C 21

M 6 — C 22

M 3 — C 20

M 7 — C 7

M 13 — P 21

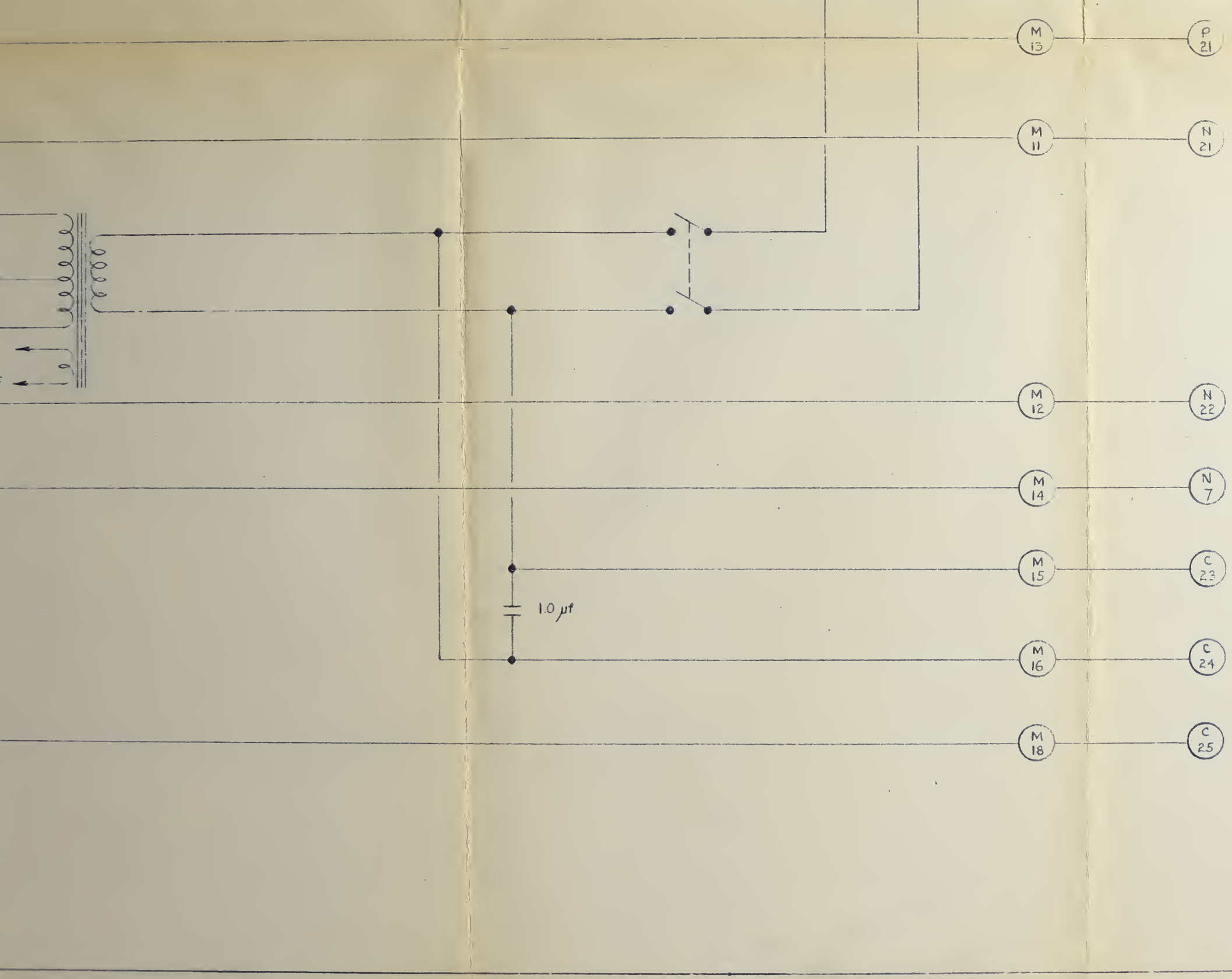


UNIVERSITY OF ALBERTA
DEPARTMENT OF CHEMICAL
AND PETROLEUM ENGINEERING

POTENTIOMETRIC MODEL

CIRCUIT DIAGRAM OF MOTOR CONTROL UNIT

SCALE NONE
DRWN: W/L
CHKD:
DATE: 21 MAR. 52


M 13
P 21
M 11
N 21
M 12
N 22
M 14
N 7
M 15
C 23
1.0 μf
M 16
C 24
M 18
C 25

B29764